15:40:56 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 06/22/93

Active

Project #: C-36-620 Cost share #: C-36-391 Rev #: 4
Center # : 10/24-6-R7441-0A0 Center shr #: 10/22-1-F7441-0A0 OCA file #:
Work type : RES
Contract#: IRI-9100149 Mod #: MEMO OF 6-14-93 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : Y CFDA: 47.070
Main project #: PE #:

Project unit: COMPUTING Unit code: 02.010.300
Project director(s):
ARKIN R C COMPUTING (404)894-8209

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 920315 to 940831 (performance) 941130 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	128,792.00
Funded	0.00	128,792.00
Cost sharing amount		36,399.00

Does subcontracting plan apply ?: N

Title: COOPERATION & COMMUNICATION IN MULTI-AGENT REACTIVE ROBOTIC SYSTEMS

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U
ONR resident rep. is ACO (Y/N): N
Defense priority rating :
supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
ISSUED TO CREATE SUBPROJECTS G-31-507 AND G-31-508. FUNDS TOTALLING $8,891 BUDGETED IN SUBS C-36-X10 AND C-36-X08 WILL BE TRANSFERED TO THE G-31 SUBS.

15:40:56 SUBPROJECTS OF MAIN PROJECT C-36-620 06/22/93

Project number	Spon/Div	Project Director	Total Contract	Project Unit	Total Funded
C-36-X08	107/000	ARKIN R C	0.00	COMPUTING	0.00
C-36-X10	107/000	ARKIN R C	0.00	COMPUTING	0.00
G-31-507	107/000		5,000.00	COMPUTING	5,000.00
G-31-508	107/000		3,891.00	COMPUTING	3,891.00

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 11/30/94

Project No. C-36-620 | Center No. 10/24-6-R7441-0A0

Project Director ARKIN R C | School/Lab COMPUTING

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. IRI-9100149 | Contract Entity GTRC

Prime Contract No. ____

Title COOPERATION & COMMUNICATION IN MULTI-AGENT REACTIVE ROBOTIC SYSTEMS

Effective Completion Date 940831 (Performance) 941130 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments
LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REQUIREMENT.

Subproject Under Main Project No. ____

Continues Project No. ____

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

Closeout Notice Date 11/30/94

Project No. C-36-620 Center No. 10/24-6-R7441-0A0_

Project Director ARKIN R C_______________ School/Lab COMPUTING______

Sponsor NATL SCIENCE FOUNDATION/GENERAL____________________________

Project # C-36-X08 PD ARKIN R C Unit 02.010.300 T
GRANT # IRI-9100149 MOD# MEMO OF 6-14-93COMPUTING *
Ctr # 10/24-6-R7441-0A1 Main proj # C-36-620 OCA CO JLB
Sponsor-NATL SCIENCE FOUNDAT /GENERAL 107/000
COOPERATION & COMMUN
Start 920315 End 940831 Funded Contract

Project # C-36-X10 PD ARKIN R C Unit 02.010.300 T
GRANT # IRI-9100149 MOD# MEMO OF 6-14-93COMPUTING *
Ctr # 10/24-6-R7441-0A2 Main proj # C-36-620 OCA CO JLB
Sponsor-NATL SCIENCE FOUNDAT /GENERAL 107/000
COOPERATION & COMMUN
Start 920315 End 940831 Funded Contract

Project # G-39-507 PD FOX J H Unit 02.010.146 T
GRANT # IRI-9100149 MOD# ADMIN. CEISMC *
Ctr # 10/11-6-P5204-0A4 Main proj # C-36-620 OCA CO JLB
Sponsor-NATL SCIENCE FOUNDAT /GENERAL 107/000
COOPERATION & COMMUN
Start 930601 End 940831 Funded 5,000.00 Contract 5,000.00

Project # G-39-508 PD FOX J H Unit 02.010.146 T
GRANT # IRI-9100149 MOD# ADMIN. CEISMC *
Ctr # 10/11-6-P5024-0A5 Main proj # C-36-620 OCA CO JLB
Sponsor-NATL SCIENCE FOUNDAT /GENERAL 107/000
COOPERATION & COMMUN
Start 930601 End 940831 Funded 3,891.00 Contract 3,891.00

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

LEGEND
1. * indicates the project is a subproject.
2. I indicates the project is active and being updated.
3. A indicates the project is currently active.
4. T indicates the project has been terminated.
5. R indicates a terminated project that is being modified.

C 36-620

To NSF Program: ____________

APPENDIX VIII

Annual NSF Grant Progress Report

PI Name: Dr. R. Arkin

NSF Award Number: IRI-9100149

PI Institution: Georgia Institute of Technology

PI Address: College of Computing
Atlanta, GA. 30332-0280

Date: 6/10/93

I certify that to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinions) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or individuals working under their supervision. I understand that the willful provision of false information or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S.Code, Title 18, Section 1001.)

Signature: ____________

Please include the following information:

1. A brief summary of overall progress, including results obtained to date, their relationship to the general goals of the award and their significance to science;
2. an indication of any current problems or favorable or unusual developments;
3. a brief summary of work to be performed during the next year of support if changed from the original proposal; and
4. any other information pertinent to the type of project supported by NSF or as specified by the terms and conditions of the grant, including a statement describing the contribution of the research in the area of education and human resources development.

If applicable, please attach a copy of any updated human subject or animal subject certification.
[Attach additonal sheets as necessary.]

Year One Annual Report

Grant #IRI-9100149

Cooperation and Communication in Multi-agent Reactive Robotic Systems

For period ending March 1993

Prepared by: Ronald C. Arkin, Principal Investigator
Mobile Robot Laboratory
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280

1. First Year Summary

We have completed a significant amount of research in the first year of this grant. Literature surveys have been conducted leading to the development of new communication mechanisms. The software simulation environment has been ported and revamped yielding extensive simulation studies. These results have attracted considerable attention within the scientific community and have resulted in two conference publications and multiple presentations at a wide range of other research venues. We also now have a preliminary working version of the multi-agent software on two of our Denning mobile robots and can demonstrate multi-agent teaming on real hardware.

2. Specific Progress and Technical Aspects

Several specific achievements have occurred during the first year of this project:

- Studies of relevant animal behavior

  A search of the ethological literature was conducted to determine the communication and social organization strategies present in simple animal systems. This resulted in a conference publication cited below. The paper is appended to this report.

- Enhancement and port of simulation environment to Sun Sparcstations

  Initially the simulation ran on a microvax II. The code was ported to faster machines and provided with better user interfaces. It was also redesigned to facilitate the testing and simulation of the large numbers of cases required for evaluation of competing multi-agent systems. Graphical tools using the public domain Khoros system from the University of New Mexico were developed for the visualization of results.

- Extensions to multiple task types

  In addition to the foraging task, we have begun investigating two new tasks. These include the consume task, that has potential utility in the context of simple assembly/disassembly operations on site. We are also looking at a grazing task which has utility for sweeping areas in simple cleaning tasks or search and rescue/surveillance operations.

- Two New Communication mechanisms analyzed

  The project started with an understanding of how tasks could be conducted in the absence of communication. We have since implemented and tested state communication mechanisms (see paper attached to report) and are now testing goal communication mechanisms. The strategy has been to take a minimalist approach to communication; starting with nothing and then adding as little as possible and assessing its impact on the society's performance.

- Development of metrics for evaluating competing systems

  Metrics such as total task completion time, average distance covered per robot, return steps per robot, and frequency of timeouts are ways in which we quantify the performance of different systems. The IEEE Robotics and Automation paper discusses our results in these terms. We are also using the concept of superlinear/sublinear performance (A team of N robots performance compared to N times the performance of a single robot) as a means for expressing relative task-achieving behavior.

- Development of Research Methodologies for Designing Multi-agent Systems

  The simulation methodology and means for expressing results provide a basis for replication by the research community at large for performance evaluation of multi-agent robotic systems of various types.

- Preliminary port to Denning robots

  The motor control for both the no communication and state communication modes have recently been ported to two of our Denning vehicles. Thus we can demonstrate preliminary results on our robotic hardware. Work remains to be done on the perceptual algorithms to be used to make each robot more self contained.

- Educational Goals

  Educational goals are being met by involving one Ph.D. student in the research (Tucker Balch) and having a local minority High School Teacher (Ms. Donna Marsh) participate in the research in the summer of 1993 as part of the Georgia Industrial Fellowship for Teachers Program (GIFT) - National Science Foundation Research Opportunity Award Program (EHR).

3. Exceptional Conditions

No significant unusual conditions were present to impede the progress of the research. The biggest concerns at this point involves the robot demonstrations. In particular, the potential for RF interference during communication between multiple active robots as well as sonar interference, although this has not proven to be a significant problem to date.

4. Other Relevant Data

4.1 Technical papers produced

Although it is early in the project, we have produced two research papers already from the preliminary results obtained in this project. Copies of the these papers are appended to this report.

- Arkin, R.C., Balch, T., and Nitz, E., "Communication of Behavioral State in Multi-agent Retrieval Tasks", *Proc. 1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, May 1993, Vol. 3, pp. 588-594.

- Arkin, R.C. and Hobbs, J.D., "Dimensions of Communication and Social Organization in Multi-Agent Robotic Systems", *From animals to animats 2: Proc. 2nd International Conference on Simulation of Adaptive Behavior*, Honolulu, HI, Dec. 1992, MIT Press, pp. 486-493.

4.2 Presentations of Research

This research additionally has been or will be discussed at several other workshops or conferences:

- **Conference on Prerational Intelligence**, "Cooperating Multi-agent Reactive Robotic Systems: Experimenting with Autonomous Agents", University of Bielefeld, Germany, Nov. 1993.

- **IJCAI Workshop on Dynamically Interacting Robots**, Panel Discussion (moderator and presenter) on Communication in Multi-agent Robotic Systems, *13th International Joint Conference on Artificial Intelligence*, Chambery, France, Aug. 1993.

- **1993 NSF Coordination Theory and Collaboration Technology Workshop**, July 1993, Arlington, VA.

- **1993 IEEE International Conference on Robotics and Automation**, "Birds do it (flock), Bees do it (swarm), Even Educated Fleas Do it (Circus)", workshop on "Needs for Research in Cooperating Robots", Atlanta, GA, May 1993.

Georgia Tech has also produced a press release regarding this research which is appended to the report.

Dimensions of Communication and Social Organization in Multi-agent Robotic Systems

Ronald C. Arkin and J. David Hobbs
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280

Abstract

Communication, social organization, task type and complexity are defining characteristics of a multi-agent system. In this paper, extensions of schema-based reactive navigation are presented as a basis for constructing multi-robot societies. As has been our tradition, ethological studies provide significant insights into the way in which robotic systems can be structured. An analysis of relevant animal behavior, a delineation of the dimensions of multi-agent systems, a description of the overall project and simulation results to date constitute the body of this paper. The multi-robot testbed on which the results of this study will be deployed is also described.

1 Introduction

Multi-agent robotic systems hold tremendous potential for applications in hazardous and dynamic environments, especially in partially modeled or unmodeled worlds. Situations found in space exploration, undersea construction, nuclear waste management and reactor maintenance, all could benefit from the development of effective teams of robots coordinating their efforts towards a common goal. Typical problems would include such things as retrieval, simple construction tasks, routine cleaning and finishing, etc.

We have previously demonstrated [3] that cooperation between robotic agents is possible even in the absence of communication. Although teaming can occur under these conditions, it does not mean that the resultant work is necessarily efficient. There are many dimensions to the teaming of multi-agents that require significant additional study. These include the role and structure of communication in these systems, social structure and organization among the agents, the nature of the task to be accomplished, and the dynamics of the target environment.

This paper describes an on-going research project funded by the National Science Foundation on cooperation and communication in multi-agent reactive robotic systems. Our research has long been influenced by psychological, neuroscientific and ethological considerations [5,6,7]. This trend continues in our multi-agent study. Studies in animal behavior and communication provide models and insights that are being used to formulate implementations on real robotic hardware. It should be recognized that the goal of our research is to produce intelligent autonomous agents and not necessarily to be faithful to the biological models upon which much of our strategies are based [6,7]. To that end, we are less concerned with the biological fidelity of ethological models than their potential usefulness for extrapolation to robotic systems. We do not attempt to reproduce actual animal behavioral patterns, but rather look towards those systems for design inspiration (not replication) in our robotic systems.

This paper is structured as follows. Section 2 provides a brief review of related work in robotic multi-agent systems, followed by an overview of our schema-based (behavioral) methodology for robot control. Section 3 surveys relevant animal social behaviors and communication systems in this context. Section 4 describes the research effort and results to date and discusses the target hardware testbed using 3 Denning Mobile Robots. A Summary and Conclusions section completes this paper.

2 Related Robotics Research

The field of robotics is still largely concentrating on the issues of single agent performance. A limited number of researchers have performed some work in the area of multiple coordinated agents; this section reviews some of their progress to date.

Fukuda's pioneering work on multi-agent systems led to the development of the CEBOT system [17], a collection of heterogeneous agents capable of assembling themselves at run-time. A more recent paper [32] describes a hierarchical communication network between the disparate agents.

Mataric [23] is studying task performance in a population of twenty homogeneous mobile robots. Tasks such as homing, flocking, and puck gathering are being examined. This system is constructed within the context of the subsumption architecture, a behaviorally-oriented reactive system.

Beni and Hackwood [20] describe a multi-agent system which possesses the ability to redistribute sensing elements within a colony. Although not ported to a real robotic system yet, they indicate that future work regarding communication would enhance performance in their circulating swarm model.

Noreils has developed an architecture capable of supporting multiple mobile robots in hazardous environments [26] which has been implemented on two indoor mobile robots. The Gofer project at Stanford University [12] involves a more traditional planner using A* search to coordinate three indoor mobile robots over a road network. Sugihara and Suzuki [31] describe a simulation method for multiple mobile robots to achieve various formations. Miller [24] describes a potential application of multiple reactive robots for use in planetary surface missions.

This research area is progressing rapidly on many different fronts. The examples above are merely representative of the large body of on-going work in this field.

The schema-based approach for mobile robot behavior, developed in our laboratory, is reviewed below prior to its discussion in the context of multi-agent systems.

2.1 Schema-based Reactive Control

Schema theory [2] provides a fruitful methodology for implementing a behavior-based robotic system. This methodology, strongly influenced by work in cognitive psychology [28,29], has been developed into a modular behavior-based control system for mobile robots [4].

Motor schemas form the basis for all activity of the robot: each motor schema corresponds to a primitive behavior. A wide range of schemas has been developed including move-to-goal, move-ahead, stay-on-path, docking, noise, avoid-static-obstacle, dodge, escape, and so on. These and other behaviors are described in more detail in [4,8,9,10].

Each behavior is concurrently active, producing a single velocity vector in response to its perception of the environment. Perceptual schemas channel the requisite perceptual information for each motor schema to perform its task. This partitioning of perceptual activity on the basis of motor behavioral need is referred to as *action-oriented perception* [5]. Each individual vector is summed and normalized and the result transmitted to the robot for execution. This stimulus-response reaction ensures timely response to changing environmental conditions. Effective robot navigation has been demonstrated in a wide-range of domains including indoor office buildings, outdoor campus settings, manufacturing environments, and in simulation for undersea and aerospace applications and rough terrain [4,8,9,5].

For the sake of completeness, formulations for several of the motor schemas used in the simulation studies follow:

- Move-to-goal: Move towards a perceptually discernible goal.

  $V_{magnitude}$ = fixed gain value
  $V_{direction}$ = in direction towards perceived goal

- Noise: a random vector used for exploration and to circumvent certain problems associated with potential fields methods [4,14].

  $V_{magnitude}$ = fixed gain value
  $V_{direction}$ = random direction for a given time persistence

- Avoid-static-obstacle: A repulsion is generated by a detected barrier to motion:

$$V_{magnitude} = \begin{array}{l} 0 \;\; for \;\; d > S \\ \frac{S-d}{S-R} * G for \;\; R < d \leq S \\ \infty \;\; for \;\; d \leq R \end{array}$$

where:
S = Sphere of influence (radial extent of force from the center of the obstacle)
R = Radius of obstacle
G = Gain
d = Distance of robot to center of obstacle

$V_{direction}$ = along a line from robot to center of obstacle moving away from obstacle

Each active schema, at each point in time, generates a single velocity vector which is combined with the outputs of the other active schemas to yield the gross motion of the robot. No memory of the environment is involved at this level - the robot reacts to its immediate perceptions in a manner consistent with its goals. The net result is intelligent emergent navigational behavior.

3 Behavioral Aspects Relevant to Multi-Agent Systems

In order to produce effective multi-agent robotic systems we feel that it is important to study biological systems first. Insights gained through these studies can often be applied to robotic systems [5,6,7]. In particular, we look to ethological studies of communication and social organization in animal groups as potential models for multi-robot systems. Five particular areas are studied: system reliability, social organization, communication, multi-agent searching and coordination.

The intent of this study is to provide an understanding of both the dimensions of the solution space for task-achieving robotic societies, and indications of potential feasible solutions within that space. It is necessary to understand the variables which affect multi-agent performance. As has been our tradition, we first look towards biological system to provide a basis for our system development. The insights gained from these studies can assist in an efficient search of the multidimensional space involved in constructing efficient and effective multi-agent societies. This section, thus, details aspects of animal behavior which we believe to have potential utility in the design of multi-agent systems. This material is of necessity terse, and it should be recognized that it is presented from the viewpoint of a roboticist and not that of an ethologist. From a biological perspective, much has been boiled away or overlooked, but to a roboticist, these sample points can provide useful information as existence proofs of functioning multi-agent systems and to serve, to a degree, as design guidelines and avenues for experimental exploration in multi-agent robotics.

An overview of several different dimensions which can affect the design of multi-agent robotic systems follows.

3.1 System Reliability

System reliability, defined as the probability that the system can act correctly, is discussed by Wilson [34] regarding groups of ants. He draws the analogy between the design of parallel-series systems from engineering to the reliability of animal social systems. When a component fails in a series system, then the whole system fails. On the other hand, if a component fails in a parallel-series system, another component can take over. Wilson proposes a theorem that redundancy should be at low levels rather than at higher organizational levels. For instance, a more reliable system will emerge when individual robots rather than whole teams of robots are redundant.

Wilson also argues that the agents must perform above a certain competence level for working in groups to be beneficial. Basically, the agents must have a certain aptitude at working together for the teamwork to pay off. A trivial example is two robots which are trying to move the same item in two different directions. A more plausible problem would be two robots which are programmed to retrieve objects in mutually harmful ways, such as one robot lifting an object while the other attempts to drag it. If they do not have a certain competence at working together, then the overall reliability of accomplishing the task will be lower than if they were working individually.

3.2 Social Organization

A natural design decision involves how the agents should be organized. Animal societies are organized in many ways (Wilson has established 10 "qualities of sociality" and Deegener has defined over 40 categories of animal societies [33]). Social networks are one of the most natural ways for humans to think of social structures. The assignment of castes or types of agents is also a natural consideration.

There are several types of social structures in animals, including the multi-level, hierarchical structure of baboons [33], the uni-level structure of a fish school [33], and the loosely structured Whiptail Wallaby mob [21].[1] Animals without multi-level hierarchies are able to conduct activities of potential application for robotics. For instance, ants are able to build complicated structures, grow food, capture slaves, wage war, transport queens, and weave leaves without a strict and complicated hierarchy. The ants utilize a heterarchical structure where there are many castes but communication between the castes is unstructured. This heterarchy allows information to flow quickly, without having the information flow up and down chains of command [16,34].

Another issue is how many different types of agents exist within the social system. Wilson [33] states that if a contingency occurs regularly, that there should be a class of agents to handle this contingency. For instance, when building a lunar base, it may be better to have separate classes of builders and retrievers of appropriate materials. On the other hand, there must be a certain redundancy within each class for reliability to be high (Sec. 3.1).

[1] Many prominent social structures are actually dominance systems ("pecking orders") which do not directly apply to robotic systems. In dominance systems, the more dominant agents have easier access to food, nesting sites, estrus females, freedom of movement, or roosting places. An example dominance system is among lions, where the dominant lions eat before the other lions. Lion cubs often die from this (by having weaker lions not reproduce, the overall strength of the species increases); robots need not compete at this level. Since the robots are not directly competing amongst themselves, these dominance systems are unnecessary.

Mode	*Directionality*	*Distance*	*Relevant Uses*
Audition	Low-Medium[5]	Far[6]	Alarm, Individuality
Luminescense	High[7]	Medium	
Chemical	Low[8]	Low[9]	Mass Communication
Reflected Light[10]	Medium	Medium	Social Distance [11]
Tactile	High	Low	
Electric	Low	Low	

TABLE I
SIMPLE COMMUNICATION

3.3 Communication

One of the most important measures of human's artificial communication systems is bandwidth (roughly, the amount of information conveyed). It appears that animals do not use a bandwidth anywhere near the range of modern day communication systems.[2] Mammals, birds, and fish have a very small range of "major displays" [27] (approximately[3] between 15 and 35). Typical ant colonies have between 10 and 20 signals [34].

Another important issue is the mode of communication. Animals use chemical, bioluminescence, reflected light, tactile, acoustic, echolocation, IR, and electric communication. Robotics and AI sensing research often stresses vision, but many animals are able to do several things with relatively simple visual systems. Table I summarizes the characteristics of some of these modalities, which can help designers choose a less expensive and more appropriate communication medium than vision.[4]

[2] Vision may be a high bandwidth medium, but the amount of information conveyed is often small, e.g., flashing a red card may only convey one bit. Our visual system may have evolved so that we can extract information from the world when we do not share an active protocol with the world.

[3] Although the exact number of bits of communication may be inexact, the bandwidth is still extremely low. Each major display may be "graded", that is, an analog signal.

[4] For more complete information on the different modes and communication information on particular animals, see [30].

[5] The directionality depends on the frequency.

[6] There are design reasons for limiting the broadcast range. In animal systems, predators may hear the broadcast. In friendly environments, there may be a problem with noise.

[7] The receiver may know exactly where the sender is, but it may be more difficult for the sender to direct the message to the receiver.

[8] Except in constant wind conditions (where the scent can be followed), or where the scent is left on an object.

[9] Except in wind.

[10] One of the reasons that reflected light may be used by animals is because of "ritualization". Ritualization occurs when a normal animal activity, such as tugging at grass with teeth, is exaggerated in form to communicate something.

.4 Multi-agent searching

; is a well-accepted fact that animals working in groups are iore effective at foraging or hunting in certain circumstances. 'he relationship that seems most prevalent in animals and iost applicable to robots is that between the distribution of he resource and the social structure of the animals. Some f the possible social animal configurations for food-seeking ivolve small versus large groups and overlapping versus non-verlapping foraging ranges. There appears to be a relation-hip between the density of the resource and the group size more abundant resources correspond with larger group sizes) nd the distribution of the resource and the searching range the more restricted the more overlap) [1,13]. A group of gents would not necessarily have to forage together. For in-tance, according to Horn's principle of group foraging, if a esource is evenly distributed it may be better for birds to orm individual partitioned territories rather than roost and orage together [33]. Useful models for ant foraging have also een developed [15,18].

In robotics, for any exploration task, the distribution of rhat needs to be located should be considered first to de-ermine the search space and search groups. For instance, ssume a robotic system is given the task to clean the hull of ship. If the barnacles are uniformly distributed, it may be est first to have the robots distribute themselves evenly and hen start cleaning. If the barnacles are dispersed and abun-ant, then larger teams should search disjoint spaces. In fact ; may be best to have a different caste of robots determine rhat the distribution should be based on the species and age f the barnacles.

.5 Multi-agent Coordination

nimals participate in many activities, sometimes alone, ometimes in groups, and sometimes in subgroups. These ctivities must be coordinated. An example is the whiptail rallaby [21], which belongs to a mob of 30-40 individuals, ut grazes with dynamically changing sub-groups. Robots hould also show a wide range of behaviors.

Finding each other becomes an issue when robots partic-pate in a wide range of behaviors alone or in sub-groups. n obvious method of finding one another is to have a cen-ral meeting place. In animals, this becomes desirable for ertain foraging strategies and for better defense. Lekking a another method where a number of individuals of the ame sex get together in a group and all make noise at the ame time. This increases the chance of an agent hearing the ocation. Table II depicts these and other strategies. (The nformation center hypothesis referred to in the table states hat colonizing birds use information from the incoming birds bout where they will go next for food. The hypothesis is not niversally accepted [19]).

The remainder of this paper discusses the framework in rhich many of these insights are being tested and developed.

Method	*When Useful*
Colony	Group Defense Information Center Hypothesis
Lekking	Multiple Agents looking for widely dispersed individual agents
Distinctive Call	Only certain agents can respond to find lost
Assembly Calls	Collect widely dispersed agents

TABLE II
SIMPLE COORDINATION

4 Project overview

The overall goal of this research is to develop a design theory or multi-agent robotic systems. Through the specification of a societal task and a particular environment, design recommendations should be available as to the number of agents that are required, the modes of communication necessary for reliable task achievement, and the social structure of the individual agents. By using an understanding of biological social systems, we expect to be able to converge on such a design theory more rapidly than would be attainable otherwise.

This section describes the first phase of an on-going NSF funded research effort in multi-agent robotics. Simulation results are presented below. The research underway involves an investigation of multi-robot systems along several different dimensions. These dimensions include the nature of communication between agents, the amount of communication between agents (bandwidth), the inter-relationships of agents (teaming effects), the nature of tasks (both simple and more complex), and the migration of the simulation results onto a working robotic system. Although these dimensions will be discussed separately in the sections below, it should be recognized that a holistic and/or synergistic effect is quite possible and the multi-dimensional space is being analyzed for such trends. The results are being evaluated in terms of task completion time, computational cost, efficiency in terms of overall utilization of resources, etc.

The simulation testbed described below provides the basis for expanding and enhancing these preliminary results prior to their migration onto working robotic systems. This testbed is an extension of the motor schema simulator system within which we test our research prior to actual robotic experimentation. It is a well developed and highly modular system that can support new schemas and communication mechanisms readily with little development overhead.

4.1 Dimensions of the Study

The project involves an analysis of the effects of communication, social organization, and task type and complexity for multi-agent robotic systems. Data points discovered in biological systems, such as discussed in Section 3, can facilitate the discovery of efficient solutions in this very complex solution space. Quantitative measures of system performance, in terms of time for completion, efficiency of completion, and other metrics (e.g., safety) are being applied to produce substantive evaluations between candidate systems.

4.1.1 Effects of Communication

It is perhaps most important to understand the impact of adding communication ability to these multi-agent units. It is crucial to determine the effects of the nature of information flow on task accomplishment. The variables include simplex or duplex communication, simple positional reports with or without acknowledgment of receipt, dynamic teaming arrangements via polling, and other more complex arrangements. The analysis is being conducted along the dimensions of direction of communication, quantity of information transmitted, broadcast or direct inter-agent communication, and specific inter-agent communication protocols.

4.1.2 Effects of Organization

Both inter-robot and intra-robot effects of organization are being studied. Intra-robot organization involves an assessment of the impact of non-symmetrical robotic agents. In the most severe case this includes pure master/slave relationships. Additionally, an analysis of how robots that possess different functional attributes (as with drones, workers, etc.) can cooperate and subdivide difficult tasks effectively forms an integral part of the overall project.

Inter-robot organization involves the impact of teaming: coordinated effort and communication between groups of multiple agents. These agents can be both symmetric and non-symmetric. The effect of team size is being assessed as well.

4.1.3 Effects of Task Type and Complexity

Thus far we have studied a simple retrieval task (below). Adding goal sequencing, something required for assembly-type tasks, is one simple extension being developed. More complex tasks such as maintenance of material flow throughout an organization, surveying, and simple construction also will serve as test scenarios for multi-agent robotics.

Other factors such as coordinated servicing (where two or more robots are required to complete a task such as a complex assembly), are also to be studied. The effects of such a *critical mass* of robots on task completion is to be analyzed in light of alternate control and communication regimes.

4.2 Simulation Results for Multi-agent Retrieval

Results have already been obtained showing multi-agent systems cooperating both in the absence of any inter-agent communication [3] and with simple communication mechanisms [25]. Three different schema assemblages have been developed representing forage, acquire, and deliver states (Fig. 1) for a simple target gathering task. Schema assemblages are aggregations of motor schemas that are parameterized to manifest an emergent behavior that is consistent with the particular state that the agent happens to be in. Much of our inspiration is derived from studies in ant behavior [15,16,18,34], although there is no attempt to simulate ant societies through this work.

An individual robot agent initially starts in a forage state, which consists of an assemblage of high-gain noise, moderate obstacle avoidance, and inter-agent repulsion. This assemblage of behaviors produces wide coverage of an area during search for an attractor object while avoiding collisions with

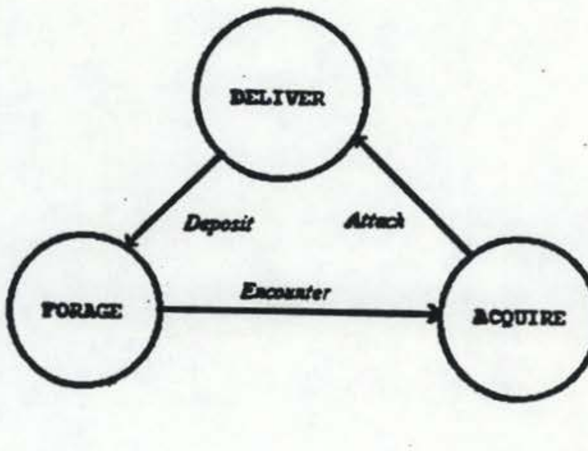

Fig. 1. Schema-assemblages for retrieval task

sensed obstacles. When an attractor is sensed within some arbitrary range of the robot, it transitions to the acquire state. This state assemblage consists of a very low-gain noise, a move-to-goal schema directed toward the attractor object, and an avoid-static-obstacle schema (Section 2.1). Additionally the inter-agent repulsion is turned down significantly, allowing multiple agents to congregate in a small area. After acquiring the attractor object, the system transitions to the deliver state, which redirects the move-to-goal to the deposit location, leaving the other schemas in the assemblage the same as in the acquire state. The specific parameterizations for these assemblages appears in [3].

4.2.1 Retrieval in the Absence of Communication

The first phase of the study, involved developing an understanding of what could be accomplished in the absence of any inter-agent communication. Ants leave chemical trails to denote where they have been, which is an indirect communication mechanism. No such information was provided here - only what was immediately perceivable to the agent (nearby goals, close obstacles, and the presence of other robots) was available. Each agent had no knowledge of what the other agent was doing and operated completely independently.

It was observed, that even in the absence of communication, coordinated completion of the task of object retrieval is possible and surprisingly efficient. The phenomena of recruitment is observed as well, something often associated with communicating agents. Recruitment refers to the collective behavior of multiple agents working together to accomplish a common task. Figure 2 depicts one example where the robots collaborate in returning a target object. In this Figure, two independent agents start near the center, both in foraging mode. After a bit of wandering, the leftmost agent senses the attractor (light disk) behind the obstacle (dark disk). It proceeds towards it and starts to retrieve it. In the meantime,

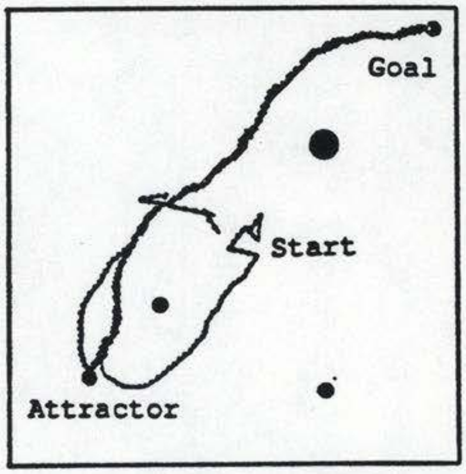

Fig. 2. Multi-agent simulation run showing retrieval of object. Dark circles represent obstacles, shaded circle is target object and goal is in upper right. (See text for explanation).

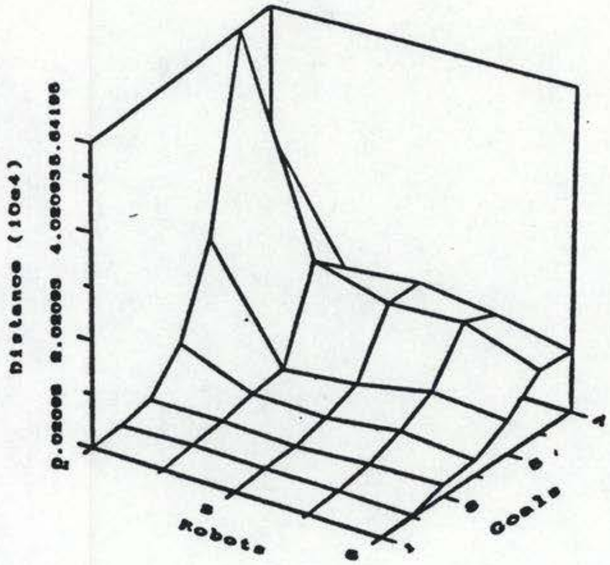

Fig. 3. Total Foraging Distance - No Communication, 10% Obstacles.

the other agent also senses the attractor. It joins the other agent in retrieving it, speeding up the return rate twofold.

Extensive simulation studies were performed to develop an understanding of the relationships between numbers of agents, numbers of goals, and system efficiency for particular environments. Several metrics have been developed reflecting speed, safety and efficiency. Figure 3 presents the total distance spent by the robots seeking out goals (foraging) for 1-5 robots retrieving 1-7 goals. This is one measure used to determine system efficiency. The more time spent foraging, the less efficient the system. The reader is referred to [3,25] for additional simulation studies.

4.2.2 Retrieval with State Communication

As discussed in Section 3.3, there are many ways in which agents can communicate with one other. The amount of information transmitted is an important consideration. As most of our research is geared for developing robots that can function in dynamic and hazardous environments, our studies have begun by exploring minimal communication methods and assessing the impact on system performance.

In the instance described here, communication between agents consisted merely of transmission of the state of the agent if it was in either retrieval or acquire mode. Under these circumstances, if an agent that was in forage state learned that a nearby agent was in acquire or retrieve state, it moved directly towards that agent. This was a more direct elicitation of recruitment. No knowledge of where the goal was given however, only the information that the communicating agent had discovered a target object. More efficient methods can be imagined such as the transmission of the coordinates of the attractor (e.g., bees), but that is not the case here.

Figures 4 shows simulation results acquired for various numbers of robots and various numbers of attractor objects when this form of communication is permitted. It can be seen that the simple communication mechanisms described above facilitate societal task accomplishment (this is the expected result). Although Figures 3 and 4 may look similar, the scales to which they are drawn are different, with the maximum value for Figure 4 being about 25% that of Figure 3, clearly illustrating the impact of even this minimal form of communication. These and other results are discussed in more detail in [25].

We intend to continue to explore alternate communication strategies including:

- Transmission of attractor coordinates when they are discovered.
- Directional versus non-directional communication.
- Communication strength.
- Distinctive signals for different actions.
- Certain types of robots being attracted to one another, and when a certain critical threshold is exceeded they call for all the other agents (assembly calls or lekking).

Reiterating, the goal of this project is to ultimately provide design guidelines for those developing multi-agent robotic systems in terms of numbers of agents, social organizations, and modes of communication. We are especially concerned with systems operating in hazardous environments where individual agents can be considered expendable. The biological studies discussed in Section 3 provide guidance for efficiently exploring the very large space of potential solutions.

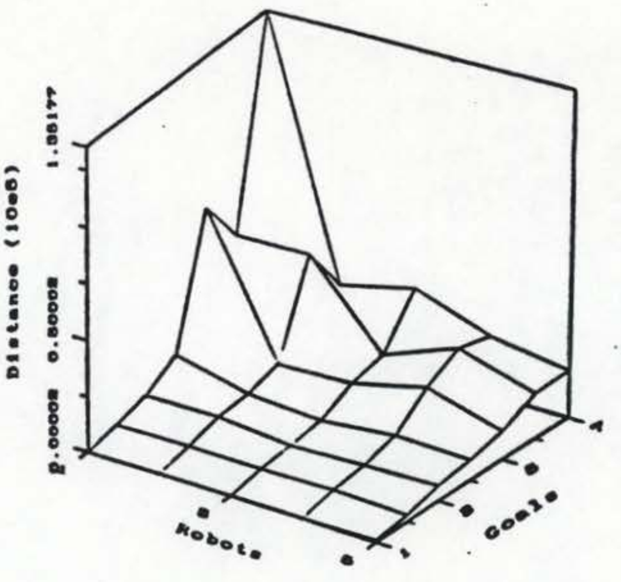

Fig. 4. Total Foraging Distance - State Communication, 10% Obstacles. Note change in scale of vertical axis from previous figure.

4.3 Hardware Configuration

The simulation work is in the process of being ported to 3 Denning Mobile Robots: two MRV-2's and 1 DRV-1. Each robot is connected to a Sun Sparc 4/40. In addition to the 24 ultrasonic sensors and shaft encoders mounted on each robot, a monochrome CCD Pulnix camera will be mounted on-board each. The cameras are to be mounted upwards and have a conic located immediately above the lens to provide a full 360 degree field of view for each robot [22]. A 19.2 kilobaud serial link using Lawn transmitters is used to maintain communication with the offboard hosts. A video link transmits the data for digitization by a Sun videopix board. Communication between the agents is conducted over ethernet.

5 Summary and Conclusions

This paper presents preliminary results from an on-going research project in multi-agent robotic systems. The relevance of ethological studies for application in this domain has been stressed and will be utilized as a guide for the development of a schema-based reactive system.

Preliminary simulation results are promising and provide solid ground for continuing work in exploring the dimensions of communication, social order, and task complexity for this work. Guidelines for the development of multi-agent robotic systems in terms of communication protocols, numbers of agents, and their structure will be a major product of this research. The system is being ported to real mobile robots for testing.

It must be remembered, that the perspective and goals of this paper are those of a roboticist, not an ethologist. No claims are made for the completeness of the ethological material presented. Nonetheless, these data points have been very helpful in determining our approach to designing multi-agent robotic systems. It is hoped that continued studies and additional interactions with colleagues in the biological sciences will provide further insights and models for potential application in robotic systems such as these.

Acknowledgments

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References

[1] Altmann, S.A., "Baboons, space, time, and energy", *American Zoologist*, 14:221-248, 1974.

[2] Arbib, M.A., "Schema Theory", article to appear in *Second Edition of Encyclopedia of Artificial Intelligence*, 1992.

[3] Arkin, R.C., "Cooperation without Communication: Multi-agent Schema Based Robot Navigation", *Journal of Robotic Systems*, Vol. 9(3), April 1992, pp. 351-364.

[4] Arkin, R.C., "Motor Schema-Based Mobile Robot Navigation", *International Journal of Robotics Research*, Vol. 8, No. 4, August 1989, pp. 92-112.

[5] Arkin, R.C., "The Impact of Cybernetics on the Design of a Mobile Robot System: A Case Study", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 20, No. 6, Nov/Dec 1990, pp. 1245-1257.

[6] Arkin, R.C., "Neuroscience in Motion: The Application of Schema Theory to Mobile Robotics", chapter in *Visuomotor Coordination: Amphibians, Comparisons, Models, and Robots*, ed. P. Evert and M. Arbib, Plenum Publishing Co., pp. 649-672, 1989.

[7] Arkin, R.C., "Modeling Neural Function at the Schema Level: Implications and Results for Robotic Control", chapter to appear in *Biological Neural Networks in Invertebrate Neuroethology and Robotics*, ed. R. Beer et al, Academic Press.

[8] Arkin, R.C. and Murphy, R.R., "Autonomous Navigation in a Manufacturing Environment", *IEEE Transactions on Robotics and Automation*, Vol. 6, No. 4, August 1990, pp. 445-454.

[9] Arkin, R.C. and Gardner, W., "Reactive Inclinometer-Based Mobile Robot Navigation", *Proc. of 1990 IEEE International Conference on Robotics and Automation*, Cincinnati, OH, pp. 936-941.

[10] Arkin, R.C. and Carter, W.C., "Active Avoidance: Escape and Dodging Behaviors for Reactive Control", *Proc. Applications of Artificial Intelligence X*, Orlando, FL, April 1992, pp. 676-688.

[11] Box, H.O., *Organisation in Animal Communities*, Butterworth, 1973.

[12] Caloud, P., Choi, W., Latombe, J., LePape, C., and Yim, M., "Indoor Automation with Many Mobile Robots", *1990 IEEE International Workshop on Intelligent Robots and Systems (IROS90)*, pp. 67-72.

[13] Carr, G.M. and MacDonald, D., "The Sociality of Solitary Foragers: a Model Based on Resource Dispersion", *Animal Behavior*, 34:1540-1549.

[14] Clark, R.J., Arkin, R.C., and Ram, A., "Learning Momentum: On-line Performance Enhancement for Reactive Systems", *Proc. 1992 IEEE International Conference on Robotics and Automation*, Nice, France, May 1992, pp. 111-116.

[15] Deneubourg, J.L. and Goss, S., "Collective Patterns and Decision-making", *Ethology Ecology and Evolution* 1: 295-311, 1989.

[16] Franks, N., "Teams in Social Insects: Group Retrieval of prey by army ants", *Behavioral Ecology and Sociobiology*, 18:425-429, 1986.

[17] Fukuda, T., Nakagawa, S., Kawauchi, Y., and Buss, M., "Structure Decision for Self Organising Robots Based on Cell Structures - CEBOT", *IEEE International Conference on Robotics and Automation*, Scottsdale Arizona, pp. 695-700, 1989.

[18] Goss, S., Beckers, R., Deneubourg, J., Aron, S., and Pasteels, "How Trail Laying and Trail Following Can Solve Foraging Problems for Ant Colonies", *Behavioral Mechanisms of Food Selection*, ed. Hughes, R., NATO ASI Series, Vol. G20, Springer-Verlag, 1990.

[19] Gotmark, F., "A Test of Information-centre hypothesis in a colony of sandwich terns *sterna sandvicensis*". *Animal Behavior*, 39:487-495, 1990.

[20] Hackwood, S. and Beni, S., "Self-organization of Sensors for Swarm Intelligence", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 819-829.

[21] Kaufmann, J.H., "Social Ethology of the Whiptail wallaby, *macropus parryi*, in northeastern New South Wales", *Animal Behavior*, 22:281-369, 1974.

[22] MacKenzie, D. and Arkin, R.C., "Autonomous Helicopter Position Determination using an On-board Integrated Vision System", *Proc. SME/MVA Applied Machine Vision Conference '92* Vol. I, Atlanta, GA, June 1992.

[23] Mataric, M., "Minimizing Complexity in Controlling a Mobile Robot Population", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 830-835.

[24] Miller, D.P., "Multiple Behavior-Controlled Micro-Robots for Planetary Surface Missions", *Proc. 1990 IEEE SMC Conference*, Anaheim, CA.

[25] Nitz, E. and Arkin, R.C., "Communication of Behavioral State in Multi-Agent Retrieval Tasks", submitted to *1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, May 1993.

[26] Noreils, F.R., "Multi-Robot Coordination for Battlefield Strategies", pre-publication manuscript from author.

[27] Moynihan, M., "Control, suppression, decay, disappearance, and replacement of displays", *Journal of Theoretical Biology*, 29:85-112, 1970.

[28] Norman, D. and Shallice, T., "Attention to Action: Willed and Automatic Control of Behavior", from *Consciousness and self-regulation: Advances in research and theory*, 4, p. 1, (R. Davidson, G. Schwartz, and D. Shapiro, eds.), Plenum Press, New York, 1986.

[29] Neisser, U., *Cognition and Reality: Principles and Implications of Cognitive Psychology*, Freeman, 1976.

[30] Sebeok, T., Ed., *How Animals Communicate*, Indiana University Press, 1977.

[31] Sugihara, K. and Suzuki, I., "Distributed Motion Coordination of Multiple Mobile Robots", *1990 IEEE International Conference on Robotics and Automation*, pp. 138-143.

[32] Ueyama, T., Fukuda, T., and Arai, F., "Configuration of Communication Structure for Distributed Intelligent Robotic System", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 807-812.

[33] Wilson, E.O., *Sociobiology: The New Synthesis*, Belknap Press, 1975.

[34] Wilson, E.O., *The Ants*, Belknap Press, 1990.

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Communication of Behavioral State in Multi-agent Retrieval Tasks

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Abstract

This paper assesses the impact on performance of a society of robots in a foraging task when simple communication is introduced. Results are obtained comparing task achievement in the absence of inter-agent communication relative to performance given the minimal knowledge of the behavioral state of fellow agents. Simple communication can result in significant performance enhancement.

Introduction

Research is currently being conducted on the use of multiple robots to solve problems in a changing workspace by having them work in parallel, and communicate when necessary. The goal of this research is to create a foundation theory which specifies, for a given task, the most reliable, efficient, and robust means of interaction between a number of robots. This means that the task will be carried out regardless of robotic failures or communication breakdown.

Related Work

Ethological studies as well as robotic implementations are both relevant to this study. This section briefly reviews some of the progress in both of these areas.

Ethology

It is clear through ethological studies that multi-agent societies offer significant advantages in the achievement of global tasks. A wide range of social structures exist: uni-level organizations as found in schooling fish, hierarchical systems as found in baboon societies [1], and caste systems typified by many insect colonies (e.g., bees). The relationships between these agents determine, to a degree, the nature and type of communication that is essential for the social system to prosper. The converse also holds in that the communication abilities determine to a degree the most effective social organizations for a particular class of agents. In [6], we discuss these issues in more detail.

For the types of foraging and retrieval task described in this particular study, societies of ants constitute a reasonably close parallel [17]. Although ants typically communicate through chemical trails left during their foraging activities, an act which this current study does not emulate (see [10] for such a simulation), the state mechanisms used for foraging, acquiring, and retrieving target objects are in strong parallel with these particular systems. A study by Franks [8] details such a process in army ants.

Robotics

A significant amount of research on multi-agent robotic systems has begun to emerge. Fukuda's early work on the CEBOT system [9] demonstrates the self-organizing behavior of a group of heterogeneous robotic agents. Beni and Hackwood's research [11] on swarm robotics demonstrates large scale cooperation in simulation. Work at MIT, by Brooks [7] and Mataric [15], shows the development of subsumption-based multi-agent teams, the latter study involving 20 small robot agents. Many other projects have been reported (e.g., [13, 14, 16]), to the point where an entire conference exists to report the results of such work [12].

Approach

The controversy between reactive control and hierarchical planning for mobile robot navigation has led to the birth of a variety of architectural designs. AuRA, [5], is one architecture which combines the modularity and speed of reactive control with the flexibility of a programmable, goal-directed planner. This architecture has been used to study a wide range of issues in mobile robotics in our laboratory.

More recently, the reactive component of AuRA has been extended to incorporate the performance of multi-agent systems. Initial work focussed on how societal task-achieving behavior can be achieved even in the absence of communication between agents [4]. The overall intent behind this research effort is to create systems capable of tackling large-scale problems that are impractical to accomplish with only one robot. Examples of tasks that would benefit from the addition of this parallelization are the distribution of materials on a shop floor, exploration of a large area, and security checking in a warehouse.

There are several dimensions along which the study proceeds [6].

- **Regarding communication:**
  Must these robots communicate in order to achieve a given goal? If so, what type and amount of communication must they convey to one another? What is an appropriate protocol for the transmission and receipt of this data? How much more is gained (quantitatively) by letting data flow between agents?
- **Regarding social organization:**
  What is an appropriate number of agents for a particular task and environment? How should these agents be organized relative to one another? Is a peer society or a caste system more appropriate?
- **Regarding task characteristics:**
  For what types of tasks is cooperation most useful? When is a single complex agent preferable over a multi-agent society?
- **Regarding environmental characteristics:**
  What is the relationship between the likelihood of failure for a particular agent with the social structure and communication mechanism for the society? What mechanisms are best-suited for highly hazardous environments?

Many of these questions are currently being explored through simulation studies, some of which are detailed in this paper. Our laboratory possesses 3 Denning Mobile Robots which will be used in the near future to demonstrate some of the principles derived from this work.

Schema-based Reactive Control

AuRA (Autonomous Robot Architecture) was designed as a hybrid approach to autonomous robot navigation. A robot's behavior is broken into independent schemas, which are each devoted to determining how the robot should react, given information about its environment [2]. A number of schemas run concurrently, depending on the task domain and the robot's intents. Each receives sensory data it needs directly and provides a contribution to the overall velocity of the robot. The results of each active schema are combined, depending on its relative influence, to produce the final motor response.

There are two primary classes of schemas: motor and perceptual. A motor schema acquires the sensory data it needs by calling a perceptual schema. These consult the sensors, process the data, and return task-specific information. Perceptual schemas act as an interface between the motor actions and the sensors.

Action-oriented perception is the underlying philosophy describing the relationship between the motor and perceptual schemas [3]. Each perceptual schema is dedicated to finding a certain piece of information specific to the motor behavior's needs, e.g., a landmark or pattern in an image. They are used to provide the motor schemas with information about relative position, location of objects, and identification of items in the scene, among other things.

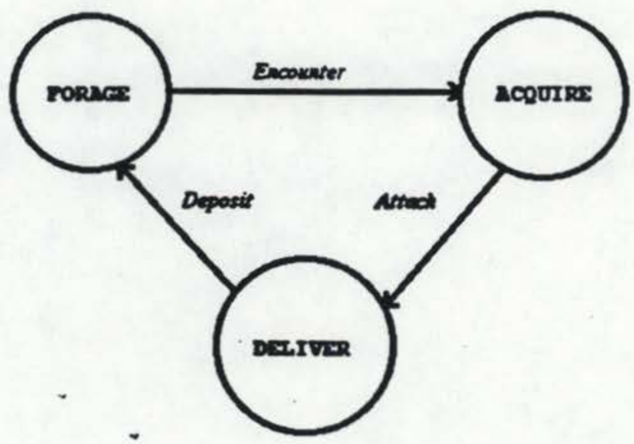

Figure 1: State diagram for an individual agent

Multi-agent Behavior in Foraging

The robots can be in one of three states: forage, acquire, and retrieve (Figure). All robots begin in the *forage* state. If there are no goals in a robot's field of view, it stays in this state and moves randomly until it finds one. If a goal comes into a robot's field of view, and it does not already have possession of one, it changes its state to *attract* and move towards it. Once it acquires the goal, its state becomes *return*, and it proceeds to carry the goal to the home base location. Upon dropping the goal, the state resets to *forage*.

The particular schemas active and their role for each behavioral state are as follows:

- forage
  - **noise** - high gain, moderate persistence to drive the robot to explore a wide area.
  - **avoid-static-obstacle**
    - for other robots - moderately high repulsion to force robots over a wide area.
    - for environmental obstacles - sufficiently high to avoid collisions.
- acquire
  - **move-to-goal** - high gain attractor towards discovered target.
  - **avoid-static-obstacle**

    * for other robots - very low gain, to allow robots to approach each other near the target without collision.
    * for environmental obstacles - as in forage.
  - **noise** - low gain, to deal with local maxima and minima [2].
- retrieve
  - **move-to-goal** - high gain attractor towards home base.
  - **avoid-static-obstacle** - same as in acquire.
  - **noise** - same as acquire.

Simulation Environment

The test environment is a simulator written in C using the X Windows graphics package and has been used to simulate multiple agents completing search-and-gather tasks. Each robot is identical (i.e., has equivalent behavioral assemblages as described above). Each agent's current state, however, is dependent on its own perception of the environment and the state of the mission.

The robotic agents search for, collect, and return targets, on a plane measuring 64.0x64.0 units, to a home base, imitating the gathering of food among colony members. Each step the robots take is represented by one loop of the program that calculates the robots' next positions. The robots are simulated holonomic vehicles with a ring of ultrasonic sensors encircling their outer hull. They have the ability to sense obstacles and other robots, to distinguish between these and the targets. They are aware of their coordinates on the grid. They are capable of navigating to goals, grasping and carrying targets, and avoiding obstacles and other robots along the way. Agents have a circular field of view with a fixed radius. There are no impassable boundaries for the grid, in order to allow the robots full freedom of movement as might occur in a real environment and so the results would not be influenced by the size of the area. However, the robots, goals, obstacles, and the home base originate in the 64x64 area.

More than one robot may carry a goal at a time, and their combined effort produces a speedup depending on the mass of the goal and the number of robots supporting it. This increase in speed is simulated by expanding the size of each step the robots take, so they cover the same distance in fewer steps. In this scenario, robots can unknowingly help one another and increase the overall speed of the mission by carrying goals simultaneously. This can be achieved without any communication between agents [4].

In Figure 2, two robots find and return two goals to the home base, in a field with 10 percent obstacle coverage. The robots do not communicate, but note that they still are able to cooperate. At the beginning, the first robot immediately finds one goal, while the other robot wanders randomly until it comes into sight of the goal (arrowed paths). It then joins the first robot and they proceed, with the goal, towards the home base (dotted path). Once they are sufficiently close to the base, they drop the first goal and begin looking for the next. They detect it, and move towards it while avoiding the obstacle in their paths. They return it together, thus completing the mission.

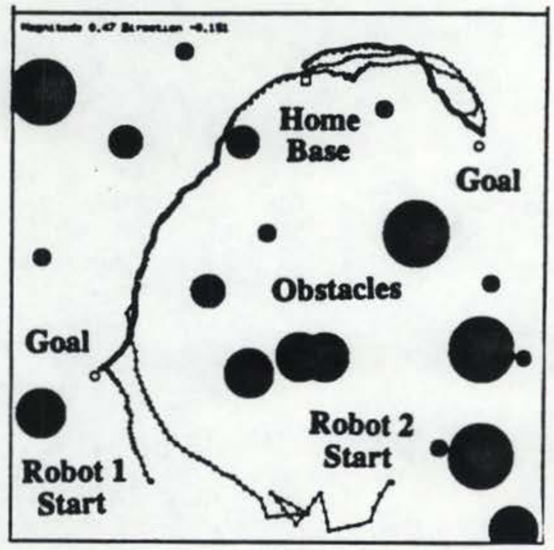

Figure 2: Two robots returning two goals without communication

Communication of Behavioral State

It is a straightforward task to modify the robot schemas to permit communication between them, enabling the assessment of the impact of various forms of interaction. An effective communication protocol used for multi-agent work should lead to an increase in the efficiency of the system, yet not slow down processing to the point that it decreases task completion speed. Also, communication in hazardous environments should not be essential for task completion, for robustness' sake. This way the job is guaranteed to be finished even in the event of a communication breakdown. Just as no robot should be dependent on another's work, no robot should completely depend on communication. In this work, communication is used as an aid, and does not form a potential barrier to goal achievement.

Inter-robot communication is simulated using shared memory, modeling a broadcast system. Robots write their current state and coordinates to the memory array at each step. The memory is accessed by a robot only when it has no goals in its field of view (i.e., during the forage state). If this is the case, the robot searches the memory for the nearest robot which is either being attracted to a goal or has acquired one already. The robot makes this robot its goal, and sets a course to follow it. Soon the follower will be in the range of the goal the other robot is tracking, and will stop accessing the shared memory and begin to be attracted by the goal. This is a minimal form of communication, and is used only to make foraging more efficient. This keeps the robots from wandering too far away from the others and the goals, while increasing the potential for cooperation and increasing the speed of global task completion. Only one robot needs to have a goal in view initially for collaboration to take place. Without this communication, the one robot may have to carry the goal by itself while the others forage randomly.

If a communication breakdown occurs, however, or no other robots have found goals, or if there is only one robot, the behavior is exactly as in the situation without communication. The job will not be affected by a loss of opportunity for interaction.

Results

Data was gathered by running simulations using one to five robots, one to seven goals, and obstacles densities ranging from 0 to 25 percent by intervals of 5 percent. Each class was run 50 times, and statistics were gathered regarding the performance.

The results from these simulations (and previous work [4]) show that this class of retrieval tasks can be solved in the absence of any inter-robot communication. In fact, it can be accomplished by one robot. However, with the addition of more robots, the performance per robot generally improves (see Figure 3). Here, performance is measured in terms of the average distance covered by each robot. Note that this depends on the relative masses of the goals, and the number of robots that find and carry them. Figure 4 shows how time to complete the overall task (another performance measure) is reduced as the number of robots increases.

Although adding robots to the environment speeds up the process, even without communication, at times it is not a great advantage, since the random wandering behavior causes some robots to lose track of the others instead of helping them. In some instances, the robots get lost and never find the goals. The simulation process times out after 2000 time cycles, which typically occurs when robots gets lost or are completely blocked by obstacles and unable to complete the task. As the number of goals and/or obstacle density increases, there is a much larger chance that the robots will not finish. In Figure 5, we show that the frequency of timeouts decreases as more agents are introduced, again without the benefit of inter-agent communication. This result is independent of the number of goals or obstacles. However, notice that the percentage either levels off or, in some cases, increases slightly as more than three robots work together.

As the number of robots increases, performance is improved, but the results show that performance is further enhanced with state communication. (Figure 6) As more robots are added, interaction continues to create improvement (Figure 7). A more comprehensive analysis (Figure 9) shows how performance varies by running the same set of simulation exercises for differing numbers of robots and goals. Figure 10 shows the data from runs using the same initial conditions as in Figure 9, but with robots communicating state.

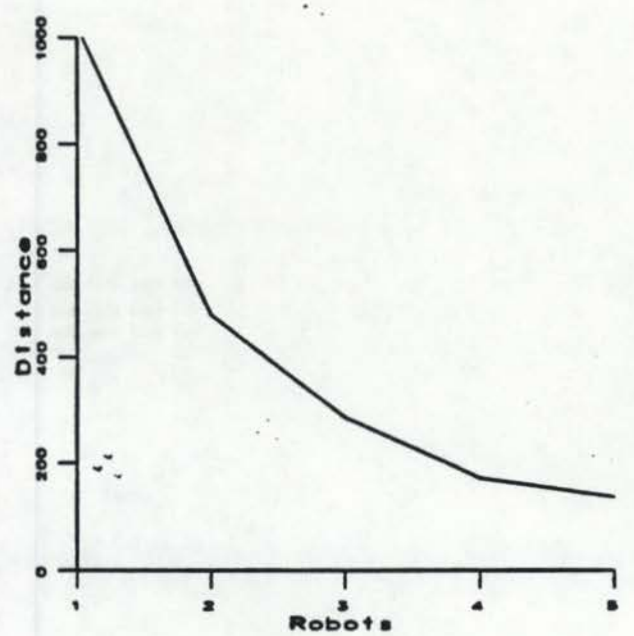

Figure 3: Average Distance Covered Per Robot, No Communication. (10% obstacles, 2 goals.)

Distance is measured as a function of the number of steps taken and the size of each step. In some cases, the total distance with communication turns out to be very close to the distance covered without the benefit of communication. In most cases, though, the advantage of reducing the time spent foraging and increasing the return speed outweighs the added attraction distance, making the overall distance less with communication than without. Comparing Figures 9 and 10 shows this difference. Similar results occur when time steps are used as the performance metric for this case.

Conclusions

Allowing the robots to communicate, if one looks only at the distance graphs, would seem to make only a modest difference. It is observed, however, that the total number of return steps that it takes each goal to get home decreases with communication (Figure 8). Considering that the distance graphs represent the *average* distance per robot, this means that more robots are being attracted to the goals, and thus more are helping carry the goals to the base. So more efficient behavior is obtained with communication, since we trade the random wandering for actual work.

More robots generally mean more efficient use of time, and an overall speedup of goal recovery. Upon inspection of the larger body of results, which give the

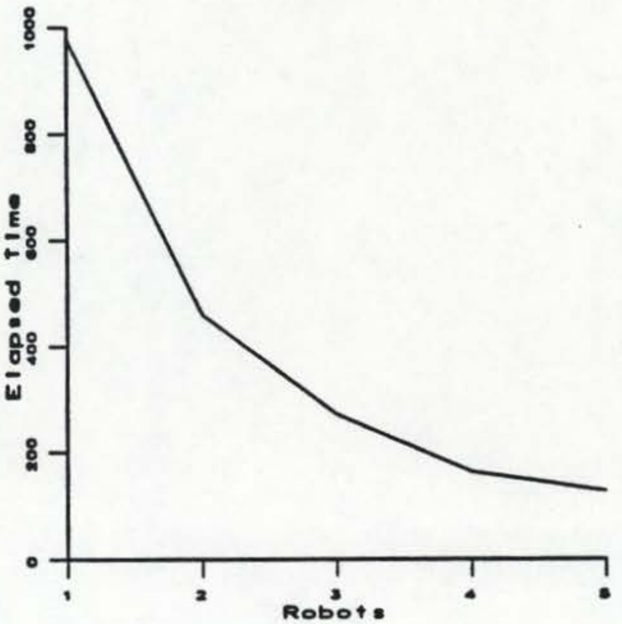

Figure 4: Elapsed Time for Task Completion, No Communication. (10% obstacles, 2 goals.)

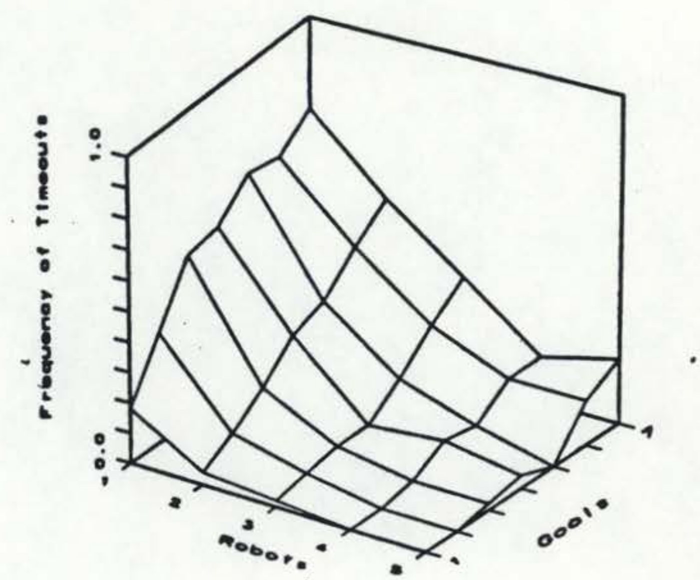

Figure 5: Frequency of Timeouts, No Communication. (10% obstacles)

percentage of timeouts per number of robots, it is apparent there is greater tendency for timing out with fewer robots. And the distance graphs tell us that by adding robots, independent of communication, the task can be accomplished faster. However, when do we have too many robots for practical use? By taking a closer look, a definite increase in performance is observed by adding one or three robots to a lone worker. The graphs then seem to level out, however, and occasionally even degrade with further additions. This occurs regardless of the number of goals or whether the robots are communicating. This leads us to believe that, for this particular task, using approximately four robots which have the ability to communicate in a minimal form is sufficient for high-quality behavior in random search and gather missions in these types of environments. Any performance benefits gained from additional robots are likely to be offset by the cost of additional agents. We intend to implement these results on the available three Denning robotic platforms available in our laboratory. The implementation will include mounting lights on each robot so that it is recognizable by others, and so that its relative heading and approximate position can be calculated by another robot. This will replace the global communication and positioning used in the simulation.

Acknowledgments

This research is supported by the National Science Foundation under grants IRI-9100149 and IRI-9113747.

References

[1] Altmann, S.A., "Baboons, space, time, and energy", *American Zoologist*, 14:221-248, 1974.

[2] Arkin, R.C., "Motor Schema-Based Mobile Robot Navigation", *International Journal of Robotics Research*, Vol. 8, No. 4, August 1989, pp. 92-112.

[3] Arkin, R.C., "The Impact of Cybernetics on the Design of a Mobile Robot System: A Case Study", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 20, No. 6, Nov/Dec 1990, pp. 1245-1257.

[4] Arkin, R.C., "Cooperation without Communication: Multi-agent Schema Based Robot Navigation", *Journal of Robotic Systems*, Vol. 9(3), April 1992, pp. 351-364.

[5] Arkin, R.C., "Towards the Unification of Navigational Planning and Reactive Control", *AAAI Spring Symposium on Robot Navigation*, Stanford, CA, 1989.

[6] Arkin, R.C. and Hobbs, J.D., "Dimensions of Communication and Social Organization in Multi-Agent Robotic Systems", *Proc. Simulation of Adaptive Behavior 92*, Honolulu, HI, Dec. 1992.

[7] Brooks, R., Maes, P., Mataric, M., and More, G., "Lunar Base Construction Robots", *IEEE International Workshop on Intelligent Robots and Systems (IROS '90)*, pp. 389-392, Tsuchiura, Japan, 1990.

[8] Franks, N., "Teams in Social Insects: Group Retrieval of prey by army ants", *Behavioral Ecology and Sociobiology*, 18:425-429, 1986.

[9] Fukuda, T., Nakagawa, S., Kawauchi, Y., and Buss, M., "Structure Decision for Self Organising Robots Based on Cell Structures - CEBOT", *IEEE International Conference on Robotics and Automation*, Scottsdale Arizona, pp. 695-700, 1989.

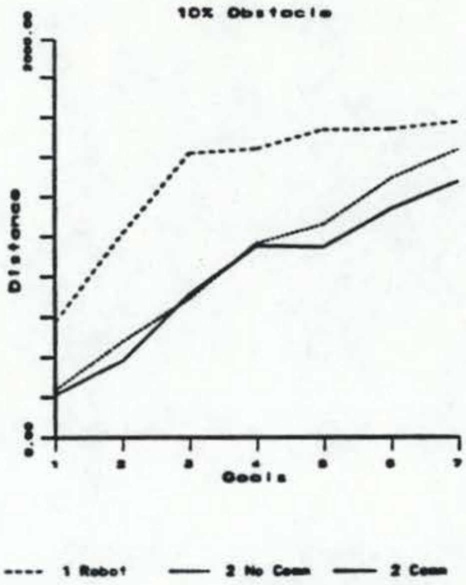

Figure 6: One and Two Robots (10% Obstacles)

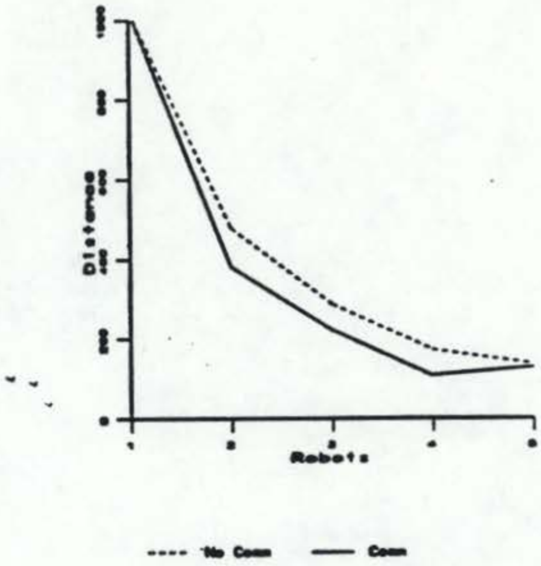

Figure 7: Average Distance per Robot (10% obstacles, 2 goals).

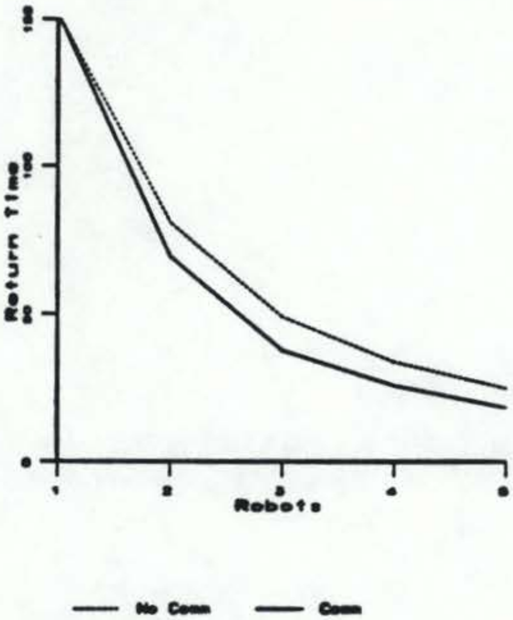

Figure 8: Return Steps per Robot (10% Obstacles - 2 goals)

[10] Goss, S., Beckers, R., Deneubourg, J., Aron, S., and Pasteels, "How Trail Laying and Trail Following Can Solve Foraging Problems for Ant Colonies", *Behavioral Mechanisms of Food Selection*, ed. Hughes, R., NATO ASI Series, Vol. G20, Springer-Verlag, 1990.

[11] Hackwood, S. and Beni, S., "Self-organization of Sensors for Swarm Intelligence", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 819-829.

[12] International Symposium on Distributed Autonomous Robotic Systems, RIKEN, Saitama, Japan, Sept. 1992.

[13] Le Pape, C., "A Combination of Centralized and Distributed Methods for Multi-Agent Planning and Scheduling", *1990 IEEE Conference on Robotics and Automation*, pp. 489-493, Cincinnati, May 1990.

[14] MacNish, C. and Fallside, F., "Temporal Reasoning: A Solution for Multiple Agent Collision Avoidance", *1990 IEEE Conference on Robotics and Automation*, pp. 494-499, Cincinnati, May 1990.

[15] Mataric, M., "Minimizing Complexity in Controlling a Mobile Robot Population", *1992 IEEE International Conference on Robotics and Automation*, Nice, pp. 830-835.

[16] Warren, C.W., "Multiple Robot Path Coordination using Artificial Potential Fields", *1990 IEEE Conference on Robotics and Automation*, pp. 500-505, Cincinnati, May 1990.

[17] Wilson, E.O., *The Ants*, Belknap Press, 1990.

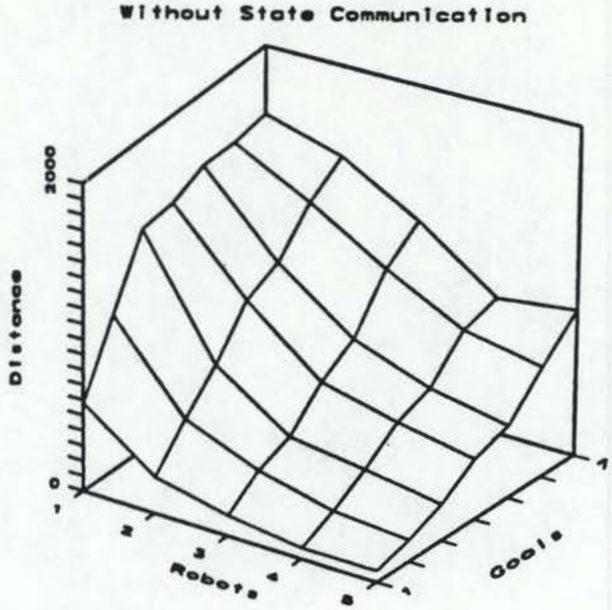

Figure 9: Total Distance Covered, No Communication (10% Obstacles)

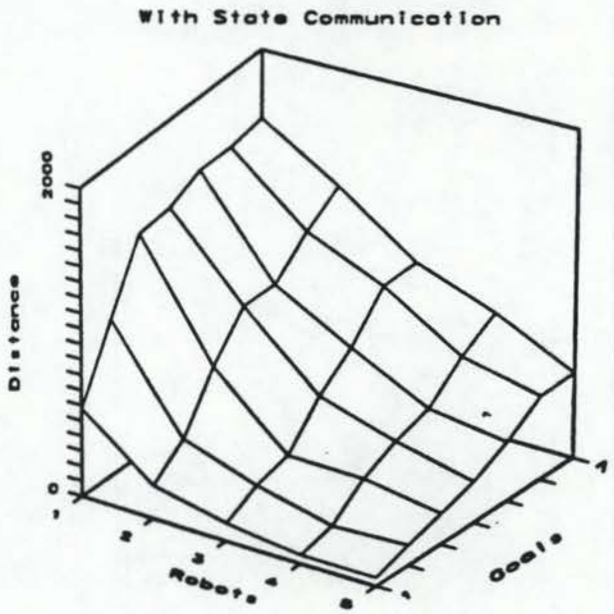

Figure 10: Total Distance Covered, With Communication (10% Obstacles)

Georgia Tech

Research News

Georgia Institute of Technology
Research Communications Office
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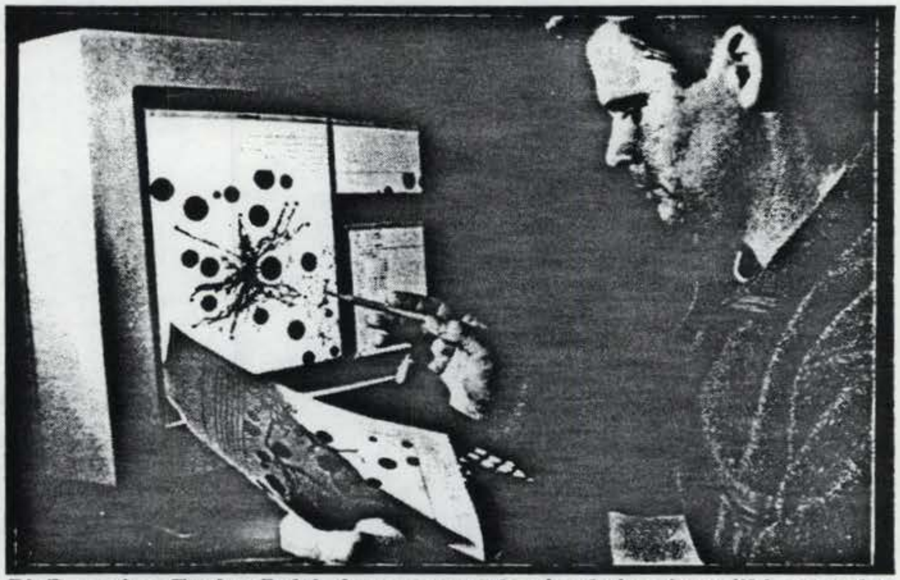
For Immediate Release
May 12, 1993

HELPING ROBOTS COMMUNICATE: RESEARCHERS DEVELOPING DESIGN THEORY OF ROBOT COMMUNICATION, SOCIAL SYSTEMS

Many people dream of the day when robot teams will work alongside or instead of humans doing everything from mowing lawns to cleaning up hazardous waste sites. Georgia Tech researchers who want to make such dreams reality are looking at the effects of communication and organization of robots on the machines' performance.

In work presented May 5 at the IEEE International Conference on Robotics and Automation in Atlanta, the researchers use a computer simulation to show that while robot teams can cooperate without exchanging information among themselves, simple communication can



Ph.D. student Tucker Balch demonstrates the simulation that will be ported to three Denning robots. (Color Slides/B&W Available)

significantly improve their efficiency. They also have found that adding robots to the work environment speeds progress up to a point. The group is porting their simulation to three Denning robots that will work as a team performing certain tasks in their lab.

"Our goal is to create a foundation theory that specifies, for a given task, the most reliable, efficient and robust means of interaction among a number of robots," said Dr. Ron Arkin, professor of computer science. "This means that the task could be completed regardless of robotic failures or communication breakdowns."

As part of the National Science Foundation-sponsored project, the group is studying the way different animal societies such as army ants, birds and fish communicate. They are applying that knowledge to the enhancement of robot communication.

FOR MORE INFORMATION:

ASSISTANCE/PHOTOS: Lea McLees or John Toon, (404) 894-3444; Compuserve, 75000,117; or Internet, lea.mclees@gtri.gatech.edu
RESEARCHER: Dr. Ron Arkin, (404) 894-8209

-OVER-

Multiple robots currently work together to perform assignments in highly predictable situations. For example, automated guided vehicles (AGVs) transport parts to other robots that assemble them. However, such robots work in clearly understood, predictable and mappable environments. Arkin and his colleagues are addressing environments that are unknown, or whose characteristics change frequently. The attributes of a mining operation involving human and vehicle traffic, for example, could not be accurately predicted or modeled.

In each simulation one to five robots, indicated on the computer screen by dotted lines showing their paths, are to retrieve up to seven targets, displayed as small circle outlines. The density of obstacles the robots must avoid, represented by black filled circles on the computer screen, ranges from zero to 25 percent of the total navigable area. Fifty random trials are run for each combination of variables.

Each robot in the simulation searches for, collects and transports targets to a designated location. The simulated robots are holonomic, or capable of moving in any direction. They are modeled after real robots that have a ring of ultrasonic sensors on their outer hulls and a 360-degree vision system. The system allows the machines to distinguish between obstacles, other robots and targets.

The simulated robots know their coordinates in the environment and can perform the three components of foraging behavior: wandering, or looking for a target; acquiring, or moving toward and picking up the target; and delivering, taking the target to a designated home base. One or more robots can carry each acquired target.

The researchers' previous findings that robots will cooperate even with no communication is borne out in the simulation. Adding one to three additional robots to a lone worker speeds up the retrieval process, even if they do not communicate. Distance covered by each robot is reduced to about 20 percent when four robots are used instead of one to search for two goals amid 10 percent obstacles, for example. Cooperation results despite lack of communication when one robot recruits others by bringing the target into their sensory fields.

In trials when they are programmed to communicate, the simulated robots do so by broadcasting their "state" -- the one of three high-level behavioral activities that they are currently engaged in -- to other robots. Robots in the wandering state listen to find the nearest robot that has spotted or retrieved a target. The wandering robot changes its behavior and makes the successful, active robot its goal. When it is sufficiently close to the target, it makes that object, and not the other robot, its goal.

"This is a minimal form of communication, and is used only to make foraging more efficient," Arkin said. "It keeps the robots from wandering too far away from the others and the goals. That, in turn, increases the potentials for cooperation and speeding up task completion."

State communication is similar to display behavior in animals, as when a peacock raises and spreads its colorful fan of feathers. The bird gets the attention of and response from its fellow animals, but does not necessarily reveal its own specific agenda.

Distance traveled, measured as the average number of steps each robot takes and the size of those steps, was on average modestly better in the communication trials than in the non-communication trials. With communication, for example, societal task completion time is about 30 percent faster when four robots are searching for two goals amid 10 percent obstacles. That indicates that more robots are being attracted to the targets and helping carry them to home base.

"Efficient behavior is obtained with communication, since we trade the random wandering for actual work," Akin said.

The researchers wrote their simulation in the C programming language and used the X Windows graphics package. In porting the simulation to the three robots in their lab, they are replacing the simulation's global communication and positioning by mounting lights on each robot, to make them recognizable to each other. That also will allow the machines to calculate each other's position and direction.

###

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FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. Howard Moraff - IRI

2. Program Name ROBOTICS AND MACHINE INTELLIGENCE PROGRM

3. Award Dates (MM/YY) From: 03/92 To: 08/94

4. Institution and Address

GA Tech Res Corp - GIT
Administration Building
Atlanta GA 30332

5. Award Number 9100149

6. Project Title
Cooperation and Communication in Multi-Agent Reactive Robotic Systems

This Packet Contains
NSF Form 98A
And 1 Return Envelope

C-36-620 2 (FINAL)

NSF Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days after the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (NSF Grants Policy Manual Section 677).

Below, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

The summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

- The primary objectives and scope of the project
- The techniques or approaches used only to the degree necessary for comprehension
- The findings and implications stated as concisely and informatively as possible

PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

I certify to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

	11/14/95
Principal Investigator/Project Director Signature	**Date**

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PART IV – FINAL PROJECT REPORT – SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1				1	1				
B. Total, Permanent Residents										
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian.										
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Hispanic										
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White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens										
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ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

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Final Report

Grant #IRI-9100149

Cooperation and Communication in Multi-Agent Reactive Robotic Systems

November 1994

Prepared by: Ronald C. Arkin (PI) and Tucker Balch (GRA)

College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280

1. Project Summary

Multiple cooperating robots are able to complete many tasks more quickly and reliably than one robot alone. A goal for this project is to determine the extent by which communication between robots can multiply their capabilities and effectiveness. In this research, the importance of communication in robotic societies is investigated through experiments on both simulated and real robots. Performance was measured for three different types of communication for multiple tasks. The levels of communication are progressively more complex and potentially more expensive to implement. For some tasks, communication can significantly improve performance, but for others inter-agent communication is apparently unnecessary. In cases where communication helps, the lowest level of communication is almost as effective as the more complex type. The bulk of these results are derived from thousands of simulations run with randomly generated initial conditions. The simulation results help determine appropriate parameters for the reactive control system which was ported for tests on Denning mobile robots.

Contents

2. Introduction and goals

This document introduces the Final Report for Grant #IRI-9100149 entitled *Cooperation and Communication in Multi-Agent Reactive Robotic Systems* This project, funded at approximately $120,000 over two years, was conducted by faculty and students within the College of Computing at the Georgia Institute of Technology. Significant contributions were made in the understanding of the role of communication in teams of robots for a broad range of tasks. This final report presents and summarizes this work.

This report is structured as follows. The remainder of this section reiterates the goals established in the original proposal in order to serve as a guideline for the evaluation of the results. The next section presents some of the technical results obtained. An assessment of our results in light of the original proposal's goals is then given. This report concludes with a discussion of the technology transfer aspects of this project and follow-on research efforts already underway.

2.1 Goals from proposal

The specific research goals we established for this project are presented verbatim below from the original proposal. They are presented to motivate the research and to provide a basis for measuring our success.

Quoting from the original proposal:

> As a result of this research, we intend to determine:
>
> - The limits of multi-agent robots in the absence of communication between agents.
> - Effective communication protocols between:
>   - Pure peer relationships
>   - Distributed master/slave relationships
>   - Multi-agent teams
>   - Non-symmetrical robotic agents.
> - Capabilities of multi-agent robotic systems for the classes of agents mentioned above.
> - An enumeration of feasible tasks and the methodology for their accomplishment by multi-agent reactive robotic systems.
> - Multiple demonstrations of working multi-agent robotic systems on actual robotic hardware.

3. Summary of Technical Results

3.1 Introduction

Robot system designers must carefully consider each component of their design. The inclusion of sensors, actuators, or additional robots must be justified by contributing to efficient task completion. Components that do not directly contribute add cost without benefit. Communication is another component of multiagent robotic systems that merits careful consideration. The question is not simply whether or not to include inter-robot communication, but what type, speed, complexity and structure. How should these design decisions be made?

As in other disciplines, a formal methodology helps the designer answer these questions. At the Georgia Tech Mobile Robotics Laboratory, such a robot system design methodology has been developed and refined for both single and multiagent robotic systems. These systems are implemented in both simulation and on mobile robots (e.g., [1,3]). The approach relies on two key points: 1) an objective metric of system performance, and 2) an iterative cycle of simulation and instantiation on real systems. Through simulation, the designer can quickly discover which sensors, actuators, and control parameters are most critical. Parameters are varied as performance is measured and compared to that of other configurations. The goal is to find a system that maximizes (or minimizes) the performance metric. Finally, the configuration is ported to a real robotic system for testing. In this project, the approach is applied to communication in reactive multiagent robotic systems.

To discover how communication impacts multiagent robotic system performance, three societal robot tasks were devised. The performance in simulation of a team of robots is measured for each of these tasks for three different types of communication. The experiments are designed so that performance for each type of communication can be compared across different tasks. In all, a six-dimensional space of task, environment, and control parameters was explored including: task, communication type, number of robots, number of attractors, mass of attractors, and percentage of obstacle coverage. The simulation results were supported by porting the control system to a team of Denning mobile robots.

3.2 Three Tasks for Robotic Societies

The task a robotic system is to perform dictates to some extent the sensors and actuators required. It is not as apparent how the task impacts control system and communication parameters. To investigate this question, three generic multiagent tasks are considered: *Forage*, *Consume*, and *Graze*.

3.2.1 *Forage*

The *Forage* task for a robot is to wander about the environment looking for items of interest (attractors). Upon encountering one of these attractors, the robot moves towards it, finally attaching itself. After attachment, the robot returns the object to a specified home base. Many ant species perform the *Forage* task as they gather food. Robots performing this task would potentially be suitable for garbage collection or specimen collection in a hazardous environment.

Figure 1a shows a simulation of two robots foraging for seven attractors and returning them to a home base (the simulation environment is described later). In the simulation, obstacles are shown as large black circles, attractors are represented as small circles, and the paths of the robots are shown as solid or dashed lines. They leave dashed lines as they wander, and solid lines when they acquire, attach, and return the attractors to home base.

The mass of the attractor item dictates how quickly a robot can carry it. The heavier the attractor, the slower the speed. Several robots cooperating can move the attractor faster, but only up to the maximum speed of an individual robot.

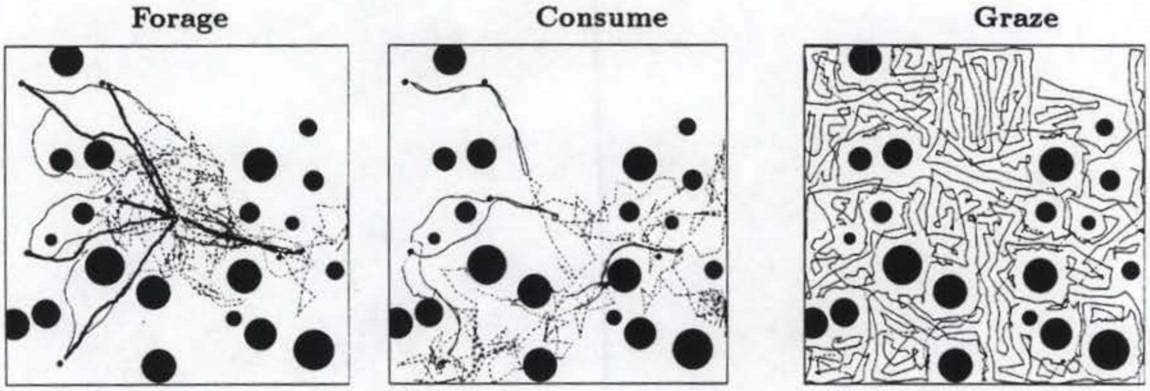


Figure 1: Simulation of Forage, Consume, and Graze with two robots and seven attractors.

3.2.2 *Consume*

Like *Forage*, the *Consume* task involves wandering about the environment to find attractors. Upon encountering an attractor, the robot moves towards it and attaches itself to the object. Unlike the *Forage* task, however, the robot performs work on the object in place after attachment. The time required to do the in-place work is proportional to the mass of the object. It is not necessary for the robot to carry the object back to home base. Applications might include toxic waste cleanup, assembly, or cleaning tasks.

Figure 1b shows a simulation of two robots consuming seven attractors. Note that this task is performed in exactly the same environment as the forage task shown in Figure 1a. The robots leave dashed lines as they wander, and solid lines when they acquire and move to the attractors.

The mass of the attractor item dictates how quickly a robot can consume it. The heavier the attractor, the more time it takes. Several robots cooperating can consume an attractor faster. For this task the rate of consumption is linear with the number of robots and has no ceiling.

3.2.3 *Graze*

The *Graze* task differs from *Forage* and *Consume* in that discrete attractors are not involved. Instead, the object is to completely cover, or visit the environment. Some familiar examples are mowing the lawn, sowing seed, and of course, cows grazing. The *Graze* task for a *robot* is to search for an area that has not been grazed, move towards it, then graze over it until the entire environment (or some percentage of it) has been covered. It is assumed that the robot possesses some means to "graze" and that it grazes over a fixed "swath." The size of the task is dictated by the proportion of environment that must be covered before completion. Figure 1c shows a simulation of two robots grazing over 95% of the environment. The robots leave dashed lines as they wander, and solid lines when they graze. Grazing robots might be used to mow, plow or seed fields, vacuum houses [11], or remove scrub in a lumber producing forest.

The size of the swath that a robot can graze, and the percentage of the area that the robot must graze over both affect how long it takes to complete the task. Multiple robots can complete the task faster if they avoid traversing already grazed areas and if they can find ungrazed areas quickly.

3.2.4 Task Parameters

Each of the task definitions include parameters that affect the speed at which a robotic system can carry them out. These are the most important:

- **Number of attractors.** Clearly the number of attractors the robots must collect or consume will affect how long it takes to accomplish the task.
- **Mass of attractors.** In general terms, an attractor's mass can be thought of as a "transportability" factor for the *Forage* task, or a "workability" factor for the *Consume* task.
- **Graze coverage.** For the *Graze* task, the total size of the area and the percentage required to be grazed directly impacts the time to cover it.

Later in this report, experimental results are presented on how each of these factors affect performance.

3.2.5 Complex tasks

For this work, only the three basic tasks and the behaviors necessary for robots to perform them are considered. The results for these tasks are important because more complex tasks are easily described as combinations of simpler ones. Consider a robot removing scrub from a forest, after working for a period of time, it must return to a refueling station. The scrub removal portion of the task is analogous to *Graze*, while refueling is similar to *Consume*.

Another complex task, *BoundingOverwatch*, is a movement tactic utilized by Army Scouts. Usually employed by two groups of two ground vehicles, it allows safe penetration into hostile areas. Each group moves forward a short distance, then waits and "covers" the other group as it moves forward. A behavior to perform *BoundingOverwatch* can be built as a more specialized and coordinated *Consume* task. Once appropriate waypoints for each group are selected, virtual attractors can be placed there. The behavior would emerge as each two element group successively moves from attractor to attractor.

Other research in our laboratory is underway which investigates how complex behaviors may be specified as combinations of basic behaviors [10]. The research includes a language which allows individual robots, and societies of robots to be described formally. Formal operators allow basic, or primitive, behaviors to be grouped into more complex assemblages. These assemblages are further combined to form the overall behavior of the robot. The language includes operators that coordinate individual robots into cooperating groups. For clarity, this report describes the robot behaviors somewhat less formally than in this related work, but the same recursive philosophy applies.

3.3 Baseline Assemblage Parameters

Experimental results were generated for the tasks described in the previous Section by comparing performance of proposed robotic systems to baseline, or control, performance results. The baseline data was computed by first selecting a reasonable set of control parameters, then running a statistically significant number of simulations. Values for these parameters are based on previous research [2]. In this section, the behaviors for executing the three tasks (*Forage*, *Consume*, and *Graze*) and their baseline parameters are described.

At the highest level, the tasks themselves are assemblages which are represented as finite state acceptors (FSAs) consisting of several states. FSAs provide an easy means for both expressing and reasoning about behavioral sets by providing formal semantics [5]. Each state corresponds to a separate assemblage in which a constituent set of motor schemas is instantiated if that particular state is active. *Perceptual Triggers* cause transitions between states. Each active motor schema has a perceptual schema associated with it to provide the information necessary for the robot to interact with its environment.

3.3.1 *Forage*

For the *Forage* task, the robots can be in one of three states: *wander*, *acquire*, and *deliver*. All robots begin in the *wander* state. If there are no attractors within the robot's field of view, the robot remains in *wander* until one is encountered. When an attractor is encountered, a transition to the *acquire* state is triggered. While in the *acquire* state, the robot moves towards the attractor and when it is sufficiently close, attaches to it. The last state, *deliver*, is triggered when the robot attaches to the attractor. While in the *deliver* state the robot carries the attractor back to home base. Upon reaching home base, the robot deposits the attractor there and reverts back to the *wander* state. Figure 2 shows the FSA for *Forage*. [1]

For each state, the active schemas and their parameters are:

- *Wander* State
  - **noise**: high gain, moderate persistence to cover a wide area of the environment.
  - **avoid-static-obstacle** for objects: sufficiently high to avoid collisions.
  - **avoid-static-obstacle** for robots [2]: moderately high repulsion to force individual robots apart and more efficiently cover the environment.
  - **detect-attractor**: perceptual schema that triggers the *acquire* state when the robot senses an attractor.
- *Acquire* State
  - **noise**: low gain, to deal with local minima.
  - **avoid-static-obstacle** for objects: sufficiently high to avoid collisions.
  - **avoid-static-obstacle** for robots: very low gain, to allow robots to converge on the same attractor and thus cooperate, but avoid colliding with one another.
  - **move-to-goal**: high gain to move the robot to the detected attractor.
  - **detect-attachment**: a perceptual schema that triggers a state transition to *deliver* when the robot is close enough to attach to the attractor.
- **Deliver State**
  - **noise**: as in *acquire*, low gain to deal with local minima.
  - **avoid-static-obstacle** for objects: as in *acquire*, sufficiently high to avoid collisions.
  - **avoid-static-obstacle** for robots: same as in *acquire*.

---

[1] This task was described earlier in [4]. The "forage" state mentioned there corresponds to the "wander" state here.

[2] **Avoid-static-obstacle** is also used for non-threatening moving objects. Other schemas such as **escape** and **dodge** can be used for non-cooperative moving objects when appropriate.

- **move-to-goal**: high gain, with home base as the target.
- **detect-deposit**: a perceptual schema that triggers a state change when the robot reaches home base.

Specific values used for schema gains and parameters in this study are listed in Table 1 (Sec. 6.3).

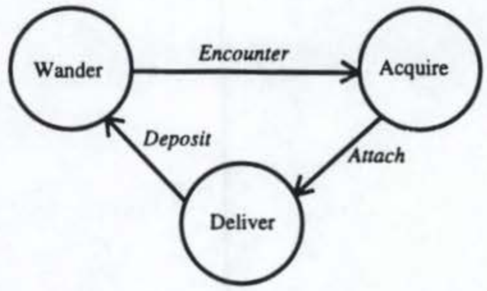


Figure 2: The Forage FSA

3.3.2 *Consume*

The FSA and behaviors for the *Consume* task (Figure 3) are similar to those used in *Forage*. In fact, the schemas and their gains are identical in the *wander* and *acquire* states. The *consume* state, however, is unique to to this behavior. In the *consume* state, only one motor schema, **consume-attractor** is activated. It reduces the mass of the attractor at a fixed rate over time. When the attractor is fully consumed (mass zero) it is deactivated and the robot transitions back to the *wander* state. Table 1 shows the schema parameters for *Consume*.

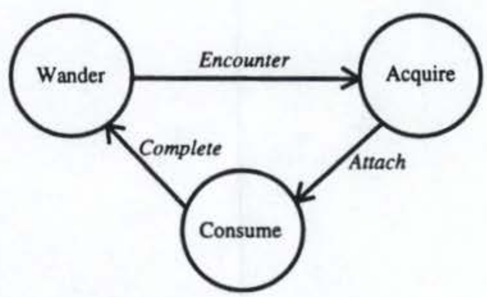


Figure 3: The Consume FSA

3.3.3 *Graze*

For the *Graze* task, the *wander* and *acquire* states are again similar to those of *Forage* and *Consume*. The primary difference is that **detect-attractor** in the *wander* state is replaced with a similar **detect-ungrazed-area** schema. **Detect-ungrazed-area** has the same fixed sensor range as **detect-attractor**, but it detects ungrazed areas instead of attractors. Each robot starts in the *wander* state and searches for ungrazed areas. Upon encountering one, it transitions to the *acquire* state and moves towards it. When the robot arrives at the graze site, it transitions to the *graze* state. The *graze* state is quite different from the corresponding states in the other FSAs. While in the *graze* state, the robot tends to move along its current heading as it "grazes" over a fixed swath of the environment. As long as there continues to be ungrazed areas directly ahead, the robot remains in the *graze* state. The active schemas for this state are:

- **noise**: low gain, to deal with local minima.
- **avoid-static-obstacle** for objects: high enough to avoid collisions.
- **avoid-static-obstacle** for robots: very low, to allow robots to graze close by, but avoid collisions.
- **probe** - moderate gain, to encourage the robot to keep moving along its current heading towards ungrazed areas.
- **graze** - performs the actual graze operation over a fixed swath.
- **detect-grazed-area** - perceptual schema that triggers a state change once the robot has completely grazed the local area.

For simulation purposes, *Graze* is implemented by maintaining and marking a high resolution grid corresponding to the environment. Initially, the entire grid is marked as ungrazed. As robots graze, they mark visited areas on the grid accordingly.

Gains and parameters for each of the schemas active in the graze state are listed in Table 1.

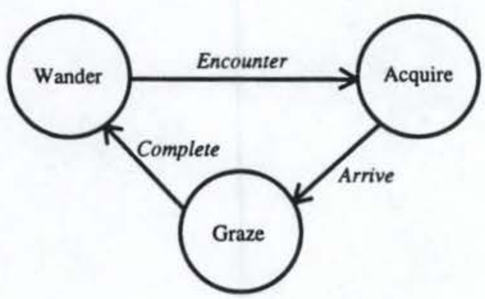


Figure 4: The Graze FSA

3.4 Forms of Inter-agent Communication

Three different types of communication are evaluated in this research. Using a minimalist philosophy, the first type actually involves no direct communication between the agents. The second type allows for the transmission of state information between agents in a manner similar to that found in display behavior in animals [13]. The third type (goal communication) requires the transmitting agent to recognize and broadcast the location of an attractor when one is located within detectable range. Each of these forms of communication is described in more detail below.

3.4.1 No Communication

For this type of multiagent society no direct communication is allowed. The robots are able to discriminate internally three perceptual classes: other robots, attractors, and obstacles. None of this information, however, is communicated to other agents. Each robot must rely entirely upon its own perception of the world. Arkin has shown in previous work [2] that this basic information is enough to support cooperation in robot retrieval tasks (*Forage*). Cooperation in this context refers to the observed phenomena of recruitment, where multiple agents converge together to work on the same task. The baseline results show that cooperation also emerges in the *Consume* and *Graze* tasks as well.

3.4.2 State Communication

When state communication is permitted, robots are able to detect the internal state (*wander*, *acquire*, or *deliver*) of other robots. For the results reported in this report, the communication is even simpler than that, where only one bit of data is transmitted: with zero indicative of an agent being in the *wander state* and one indicating that it is in any state other than *wander* (i.e., *acquire*, *deliver*, *consume*, or *graze*). In [4], this type of communication was shown to provide a distinct advantage over no communication for performance of the *Forage* task. Communication is often considered a deliberate act, but state communication is not necessarily "intentional" since information can be relayed by passive observation. The sender does not necessarily explicitly broadcast its state, but allows others to observe it. In nature this type of communication is demonstrated when an animal changes its posture or external appearance, such as a dog raising its hackles or exhibiting flight behavior in response to fear.

To take advantage of state information in reactive control, the behavioral assemblages for each task are modified slightly. From a robot's point of view, the most important states to look for in another robot are those where the other robot has found an attractor or an area to graze; that means that the other robot has found useful work. If the robot goes to the same location, it is likely to find useful work as well, or at least be able to assist cooperatively. The appropriate states are *acquire*, *deliver*, *consume*, or *graze* ; in the *wander* state the robot has not yet found any work to do.

For all three tasks, the behaviors are modified so that a robot will transition to *acquire* if it discovers another robot in *acquire*, *deliver*, *consume*, or *graze*. Since the robot may not yet know the location of the attractor, it follows the other robot instead. Once the attractor is detectable it heads directly for it.

3.4.3 Goal Communication

Goal communication involves the transmission and reception of specific goal-oriented information. Implementation on mobile robots requires data to be encoded, transmitted, received, and decoded. Goal communication differs from the other two levels in that the sender must deliberately send or broadcast the information. A natural example of this type of communication is found in the behavior of honeybees. When a bee discovers a rich source of nectar, it returns to the hive and communicates the location with a "dance" which encodes the direction and distance from the hive to the source.

For reactive control, goal communication is implemented by modifying the behavioral assemblages in the same manner as described for state communication. However, instead of following the transmitting robot that discovered the attractor, a receiving robot moves directly toward the location of the attractor. The intent is that the agent may now follow a more direct path (beeline) to the attractor.

This very rudimentary form of communication only broadcasts the goal that the transmitting agent is involved with. Another mode of communication, not yet explored, involves the transmission of all detected attractors independent of whether the transmitting agent is already acquiring or delivering one. This would present more options for the receiving agent, perhaps choosing to move to the closest attractor independent of whether or not the transmitting agent would benefit from its help. This additional form of communication is left for future work.

3.4.4 Explicit versus Implicit Communication

The implementation of goal and state communication requires explicit signaling and reception of the communicated information. State communication can be implemented simply by mounting a binary signal atop the robot which is either on or off depending on the robot's internal state. This communication, although trivial, is explicit as it requires the deliberate act of invoking the signal.

Information pertinent to cooperation might be gathered by other means as well. The internal state of a robot could be inferred by observing its movement (e.g., recognizing a robot in the *wander* state due to apparent random movements), thereby placing a larger perceptual burden on the receiving agent. Robots can also communicate through their environment. In the graze task, robots leave evidence of their passage since the places they visit are modified. This fact is observable by the other robots. These types of communication are referred to as *implicit* since they do not require a deliberate act of transmission.

Implicit communication was found to be an important mode of cooperation in simulations of the graze task. Since this communication emerges from the interaction of the agent and the environment, it cannot be "turned off." Thus comparative analyses of performance with and without implicit communication are not meaningful.

3.5 Simulation Environment

The simulation environment should provide an accurate estimate of robot performance in the real world. Simulation is important because it offers a means to test many robot system configurations quickly. To be useful, the simulation must report performance in terms of the prescribed performance metric and realistically emulate the environment and the robot's interaction with it. Furthermore, the simulation must allow hardware, control, and environmental variables to be readily manipulated.

The test environment for this research is written in C using the X Windows graphics package. The simulator has been a useful tool for other research in the Mobile Robot Lab at Georgia Tech, including [4,8,14,11,7] among others. Results generated in this simulation environment have routinely been demonstrated on actual mobile robots (e.g., [1,6,3,7]). Except for minor changes [3], the present simulator is the same one used in these earlier projects. The simulator may be run in a visual mode, or in a text-only mode. The visual mode is used primarily for debugging and qualitative accessments. The text-only mode is used for multiple runs to gather extensive statistical data.

Each robot is an identical holonomic vehicle which is controlled by one of the task assemblages described above. Each agent's current state, however, is dependent solely on its own perception. The robotic agents execute their tasks in a 64 x 64 unit environment. The units are dimensionless, but for convenience of comparison to real robot implementations they represent one foot. Time is measured in steps. Each step is one iteration of the program that calculates the robots' next positions. The robots are able to sense their location in the environment, and detect obstacles, attractors and other robots within a fixed radius field of view. They are able to grasp and carry attractors, consume attractors, or graze as the task dictates. The simulation automatically enforces the limits and rules set forth in the task specifications, as well as sensor/actuator limits. The robots are allowed to move without restriction within the

[3] The differences are in three areas: 1) How test scenarios are generated, 2) What happens when robots fail to complete the task, and 3) Restrictions on robot movement. In the new simulator, obstacles are not allowed to overlap one another. Previously, this was allowed, resulting in a less accurate accounting of obstacle coverage. For this research robots are initially placed in the center of the environment, at home base. In earlier research they were placed randomly about the environment. The authors believe a single starting location for all robots is more likely in real world implementations. The previous simulator allowed runs not to exceed a maximum of 2000 steps. If a run exceeded this time limit it was halted and discarded. Here the limit is raised to 8000 steps and runs that timeout are counted as taking 8000 time steps. In the new simulator, robots are not allowed to move outside the visual boundaries of the environment, as was previously the case.

64 x 64 environment, but they may not move outside of it.

3.5.1 The Performance Metric

What is "performance"? Since one goal of this research is to report the impact of communication on robotic societies, performance must be objectively measurable. Selection of a performance metric is important because these metrics are often in competition - i.e., cost versus reliability. Some potential metrics for multiagent robotic systems are:

- **Cost** - Build a system to accomplish the task for the minimum cost. This may be appropriate for many industrial tasks. Use of this metric will tend to reduce the cost of the system and minimize the number of robots used.
- **Time** - Build a system to accomplish the task in minimum time. This metric will lead to a solution calling for the maximum number of robots that can operate without interference.
- **Energy** - Complete the task using the smallest amount of energy. This is appropriate in situations where energy stores are limited, e.g., space or undersea applications.
- **Reliability/Survivability** - Build a system that will have the greatest probability to complete the task even at the expense of time or cost. This may be useful for certain strategic military applications.

The task metric can also be a numeric combination of several measurements. Whatever the metric is, it must be measurable, especially in simulation. For this research, time to complete the task was chosen as the primary performance metric. It is easily and accurately measurable and conforms to what is frequently thought of as performance. No claim is made however that this is the "best" metric; robot path length or energy consumption may be equally useful. In the simulation studies described herein, performance is measured by counting how many iterations the simulation program executes before the task is completed.

There are a few initial conditions for some tasks that prevent the robots from completing it. For example, if an attractor was somehow placed within a circle of obstacles, the robots would never be able to reach it. Such a scenario is not solvable by any robot system without the capacity to move the obstacles. Other scenarios, however, may ultimately be solvable, but may potentially defeat the purely reactive strategies presented here. To provide for these situations, the simulation is allowed to continue for 8000 steps before failure is declared. Since most runs complete in less than 2000 steps, it is highly likely that the system will *never* complete the task if it does not do so before failure is declared. The objective is to evaluate the impact communication makes on performance, so it is not important to know why the system failed, just to measure how it improves with communication. In cases of failure, the run is recorded as having taken 8000 steps. This approach reports optimistic performance since the run might never have completed (infinite steps). But, to show improvement over a failure case, the system must actually complete the task *and* in less than 8000 steps.

3.5.2 Environmental Factors

As much as can be known about the target system's operating environment should be incorporated into the design process for the control system. If these factors are known *a priori*, they can be included in the simulation. Important environmental factors include:

- **Mobility factors:** Is the terrain mountainous or flat? What percent of the environment is served by roadways?
- **Obstacle coverage:** What percent of the environment is cluttered with obstacles?
- **Metric *a priori* knowledge:** Does the robot have a good map of the area or is it completely unknown?
- **Static or dynamic:** Is the environment filled with moving objects, thus reducing the utility of maps, or is the environment a static one?

For this study, a static flat environment with randomly scattered obstacles is assumed. No *a priori* knowledge of the obstacles' location is available. Obstacle coverage is varied from 5% to 20% of the total area, with 15% as a baseline.

3.5.3 Motor and Sensor Constraints

As a step in the robot system design methodology, realistic bounds on the expected motor and sensor capabilities of robots are set. These bounds help reduce the search space for an optimum solution. The affect of communication on performance is the main thrust of this research, so fixed values representing the expected performance of the robots were used. If the goal were to determine optimal sensor or motor requirements, those parameters could be varied as well. Table 1 shows the experimental motor and sensor values used in the simulations.

3.6 Baseline Results and Analysis Tools

To build a baseline database of performance measurements, a configuration of environment, control, and task parameters was selected empirically (Table 1). The baseline database serves as a control for comparison in the evaluation of the communication experiments described below. The database is generated by running the simulation using the baseline configuration parameters for each of the three tasks: *Forage*, *Consume*, and *Graze*. For each task, the number of robots and the number of attractor objects (or percentage of graze coverage) is varied. For each combination of robots and attractors, a measure of performance is taken by timing runs on 30 different randomly generated scenarios. Overall performance is the average of those 30 runs. For each run, the simulation records the number of steps taken, and whether or not the run timed-out (failed).

The baseline performance measurements were made with no communication allowed between the robots. This control is then compared with the performance in each of the three tasks when state or goal communication is allowed. From these comparisons, one can see quantitatively how these modes of communication impact performance.

3.6.1 Basic Performance

Performance data is visualized as a 3-dimensional surface with the X axis reflecting the number of robots and the Y axis indicating the number of attractors or percent coverage[4] (see Figure 5). The Z, or height, axis shows the average time to complete the task for that combination of robots and attractors (smaller numbers are indicative of better performance).

The plots for all three tasks share a similar shape. Notice that the back left corner is the highest point on the three surfaces. This is expected since that location represents the case where one robot by itself must complete the most work (seven attractors for forage and consume, 95% coverage for graze). Similarly, the right front is the lowest point, since the largest number of robots (five) complete the least amount of work (one attractor). It is also apparent for all three tasks that performance initially improves sharply as more robots are added, but then tapers off. In some cases, performance does not improve much at all with more than 4 robots. This is important if robots are expensive.

To illustrate, suppose a robotic system for the *Forage* task should be both fast *and* inexpensive. Performance is then a combination of the time to complete the task and the cost of the system. Ultimately, the designer must balance the importance of cost versus speed of completion, but one approach is to amortize the cost of the robotic system over its expected lifetime. Thus the cost of one run is the overall cost divided by the expected number of runs. For this example, suppose the amortized cost of each robot per run is valued the same as 300 time steps. Then if N is the number of robots, and T is the time to complete the task, the overall performance is:

$$P = N * 300 + T \tag{1}$$

Using timing measurements taken for *Forage* and adding in amortized cost, a three dimensional surface is generated for the new performance metric (Figure 6). A system with two robots is generally best for three or more attractors. If the environment is expected to contain only one or two attractors, one robot is the best choice. Even though more robots may be faster, the overall goals of the designer may call for fewer.

[4]For *Graze*, the percent of area to be grazed is varied in increments of 13.57%. This allows the difficulty to be varied in seven discrete steps from 13.57% to 95%. Results can be directly compared to *Forage* and *Consume* tasks with one to seven attractors.

Factor	Baseline	Experimental Range
Task Factors		
Number of attractors	-	1 to 7
Mass of attractors	5 avg	1 to 8
Graze Coverage	95%	13% to 95%
Environmental Factors		
Obstacle Coverage	15%	10% to 25%
Obstacle radius	-	1.0 to 4.0
Number of Robots	-	1 to 5
Sensor and Motor Constraints		
Maximum Velocity	2 ft/step	fixed
Attractor Sensor Range	20 ft	fixed
Obstacle Sensor Range	20 ft	fixed
Communication Range	100 ft	fixed
Communication Type	No	No,State,Goal
Graze Swath	2 ft	fixed
Consume Rate	0.01 units/step	fixed
Control Parameters		
Obstacle Sphere of Influence	5 ft	fixed
Obstacle Repulsion Gain	1.0	fixed
Robot Repulsion Sphere	20 ft	fixed
Robot Repulsion Gain (*wander*)	0.5	fixed
Robot Repulsion Gain (*acquire*)	0.1	fixed
Robot Repulsion Gain (*deliver, graze*)	0.1	fixed
Move-to-Goal Gain (*acquire*)	1.0	fixed
Move-to-Goal Gain (*deliver*)	1.0	fixed
Probe Gain (*graze*)	1.0	fixed

Table 1: Experimental Parameter Values. Unless noted otherwise, the values are the same for all three tasks.

3.6.2 Speedup

Another effective tool is *speedup* measurement. A plot of speedup reveals how much more efficient several robots are than just one in completing a task. If $P[i,j]$ is the performance for i robots and j attractors, the speedup at that point is:

$$S[i,j] = \frac{\frac{P[1,j]}{i}}{P[i,j]} \tag{2}$$

So, if two robots complete the task exactly twice as fast as one robot, speedup is 1.0 (higher numbers are better). Mataric introduced a similar metric of robot performance in [12]. Anywhere speedup is equal to 1.0, the performance is said to be *linear*. *Superlinear* performance is greater than 1.0, and *sublinear* is less than 1.0. Realize, however, that in some cases more robots will be faster for actual task completion time, but still offer sublinear speedup.

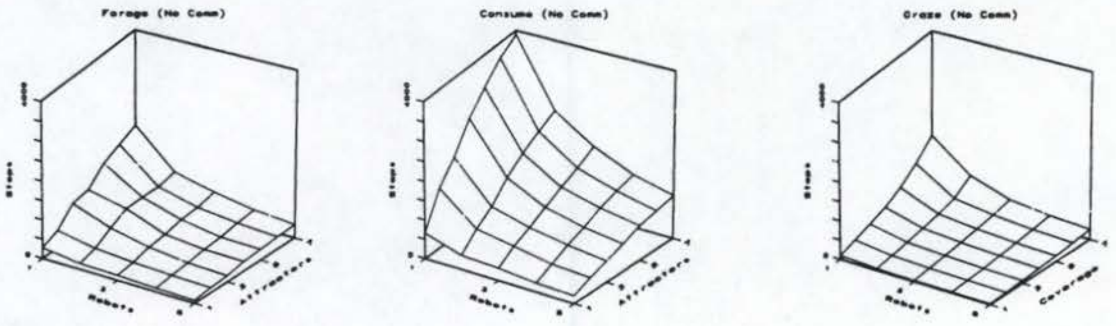


Figure 5: Time to complete the *Forage*, *Consume*, and *Graze* tasks for one to five robots and one to seven attractors with no communication.

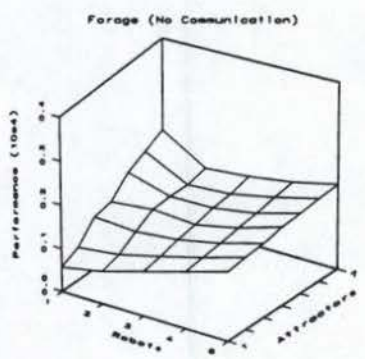


Figure 6: Optimizing in *Forage* for time and cost. Performance here is defined as time to complete the task plus the number of robots times 300 (no communication).

Figure 7 shows speedup plots for *Forage*, *Consume*, and *Graze* without communication. Note that speedup for all tasks is generally higher for larger numbers of attractors. Researchers in other branches of computer science have found that randomized search tasks are often completed in superlinear time on parallel systems [9]. Since the *wander* behavior used in all three tasks essentially solves a randomized search task, it is not surprising that performance is superlinear when this behavior is heavily utilized, as is the case when there are large numbers of attractors.

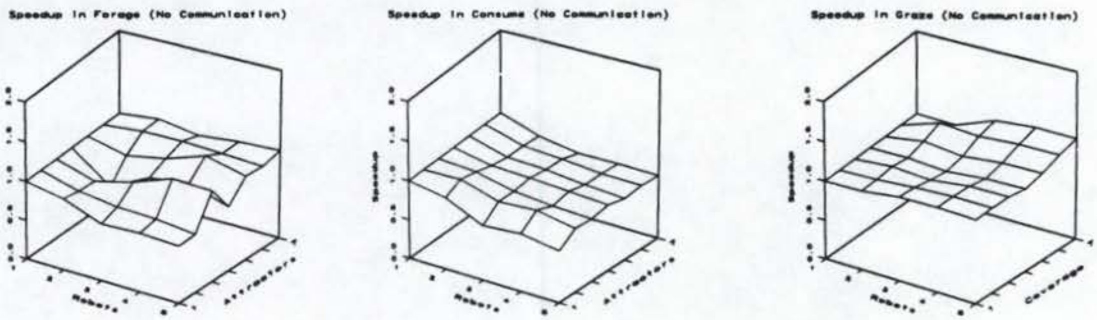


Figure 7: Speedup in the *Forage*, *Consume*, and *Graze* tasks for one to five robots and one to seven attractors (no communication).

Surprisingly, speedup in the *Consume* task is sublinear at all but one point (Figure 7b). The behavior in the *consume* state can at most offer linear speedup (the limit is set by the specification of the task). So an environment with massive attractors will force the speedup to be limited near 1.0. This hypothesis was tested by reducing the average mass of the attractors, then rerunning the simulations. In the baseline runs, attractor mass varies from 2.0 to 8.0 units, but for these experimental runs, mass was reduced to 1.0 to 4.0 units. Reducing attractor mass allows the robots to spend more time wandering (a superlinear task) instead of consuming (at most linear). The speedup for *Consume* with lower mass attractors is shown in Figure 8. At every point on the surface, speedup is better for low mass attractors than for high mass. In fact, in many cases speedup is superlinear.

Speedup in the *Graze* task is superlinear at all but three points on the surface (Figure 7). In the very worst case, speedup dips to 0.97. Situations requiring a high percentage of graze coverage result in the best speedup; the peak is 1.21 for five robots and 95% coverage. In cases where high graze coverage is required, robots spend more time in *wander* as they look for the last bit of area to graze. Again, since *wander* is a superlinear time task, the best speedups should be expected for those regimes.

Speedup results are summarized in Table 2.

3.6.3 Timeouts

Task	Avg. Speedup	Best	Worst
Forage	0.93	1.15	0.64
Consume	0.82	1.01	0.65
Consume(low mass)	0.89	1.26	0.66
Graze	1.07	1.21	0.97

Table 2: Summary of speedup data for three tasks.

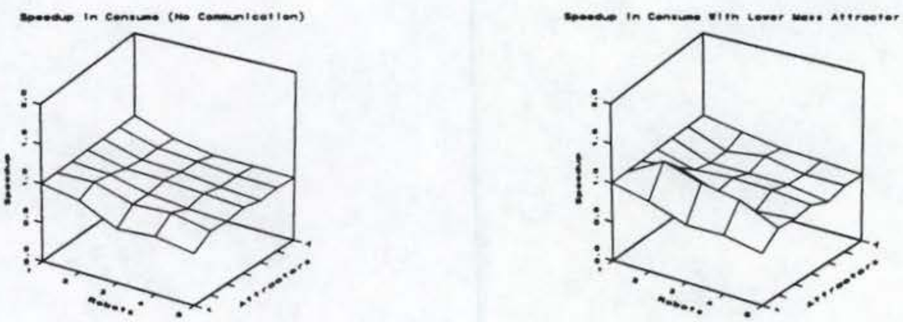


Figure 8: Side by side comparison of speedup in the *Consume* task (without communication). Performance with attractors of average mass 5.0 (left) and 2.5 (right).

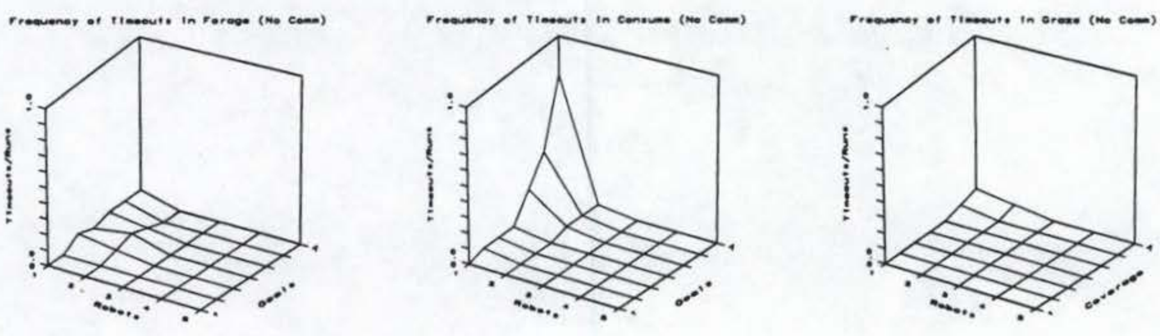


Figure 9: Frequency of timeouts (percent) in the *Forage*, *Consume*, and *Graze* tasks for one to five robots and one to seven attractors (no communication).

A *timeout* occurs when a simulation run exceeds a time limit (for these experiments, the limit is 8000 steps). A timeout mechanism is necessary to avoid lockups in infinite loops in the event the society is unable to complete the task for that particular world. Frequency of timeouts for each combination of robots and attractors is measured and plotted in Figure 9. The frequency of timeouts serves primarily as a measure of data quality. In situations where timeout frequency is higher, the experimenter cannot know for sure how long the runs would have taken if they were allowed to complete. Some runs may have completed while others may have run indefinitely. When there are relatively few timeouts, the performance is known with greater certainty. As would be expected, most timeouts occur when fewer robots must solve a task with more attractors or a higher graze coverage requirement.

3.6.4 Summary of Baseline Results

Baseline results serve as a control for experimental comparison in assessing the impact of other communication modes on performance. It is important to derive and understand fully these basic results before testing more complex robot configurations. Important results for the baseline configuration are:

- For a given number of attractors, more robots complete a task faster than fewer robots.
- For a given number of robots, it takes longer to complete a task with more attractors.
- Some performance metrics may result in a system that is optimized with lower numbers of robots than for other metrics.
- Speedup is greater in scenarios where larger numbers of attractors are present.
- Speedup in the *Consume* task is mostly sublinear, but can be superlinear for lower mass attractors.
- Speedup in the *Graze* task is mostly superlinear.
- Timeouts occur more often for low numbers of robots and high numbers of attractors.

3.7 Results with Communication

3.7.1 Communication in the *Forage* Task

Figure 10 shows a typical simulation run of two robots foraging for seven attractors with no, state, and goal communication. Inspecting the images from left to right reveals an apparent improvement in the "orderliness" of the robots' paths. The quantitative experimental results summarized in Table 3.7.3 confirm these qualitative impressions.

Figure 5a shows a typical performance plot for *Forage*, in this case for no communication (better performance is lower). Each data point represents 30 different simulation runs.

The plots for no, state, and goal communication are quite similar in contour but there is improvement in performance evidenced by lower surfaces as the communication becomes more complex. The statistical analysis in Table 3.7.3 summarizes these observations.

To quantify the difference between performance with and without communication, a performance ratio plot is computed (Fig. 11). At each point, the performance with communication is divided by the performance without communication. Results greater than 1.0 imply improved performance. For instance, a value of 1.1 indicates 10% improvement. For all the cases tested, State communication improved performance in the *Forage* task an average of 16%. On the average, goal communication is 3% better than state communication in the *Forage* task.

3.7.2 Communication in the *Consume* Task

The impact of communication on performance of the *Consume* task is similar to that in *Forage*. Figure 12 shows a typical simulation of two robots consuming seven attractors with no, state, and goal communication. A surprising result is that the simulation with goal communication actually takes longer than the one with state communication. This slight increase in run time with goal versus state communication is typical for this task.

A representative example of the basic performance data for simulations of the *Consume* task is plotted in Figure 5b. Again, the contours for all three forms of communication are quite similar. A comparative analysis reveals that on the average, state communication offers a 10% performance advantage over no communication. Goal communication is 4% worse on the average than state communication. Goal communication, however, is still 6% better than no communication at all. Table 3.7.3 summarizes these results.

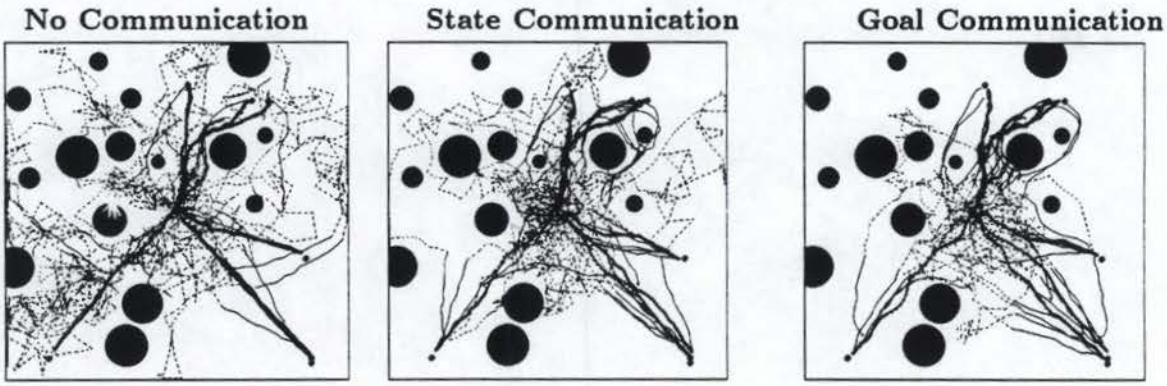


Figure 10: Typical run for *Forage* task No (left), State (center), and Goal (right) Communication. The simulations required 5145, 4470 and 3495 steps, respectively, to complete.

Recall that speedup in the *Consume* task is linked to attractor mass. Attractor mass may also impact the benefit of communication. Analysis of the data from runs with low mass attractors reveals that goal communication performance is almost indistinguishable from that of state communication (1% worse). Future research may determine if this result is just an anomaly or if environmental and task parameters might shift this trend.

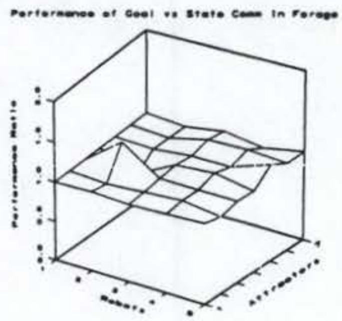


Figure 11: Performance ratio plot for the *Forage* task for Goal versus State communication.

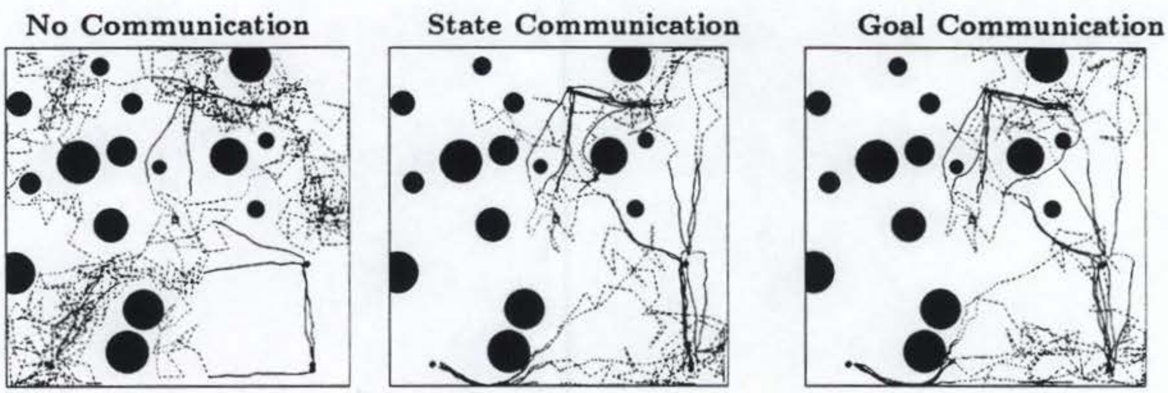


Figure 12: The *Consume* task with No, State, and Goal Communication. The simulations required 9200, 8340 and 8355 steps, respectively, to complete.

3.7.3 Communication in the *Graze* Task

The surprising result from Graze task simulations is that communication hardly helps at all. Plots of basic performance data for each of the different levels of communication are not shown because they are visually identical (see Figure 5c for the case with no communication). On average, state communication is only 1% better than no communication. Performance with goal communication is virtually indistinguishable from that with state communication (0% difference). Table 3.7.3 summarizes these results.

As robots graze they inevitably leave a record of their passage: the graze swath. This physical change in the environment is actually a form of implicit communication. The robots leave marks that advise others where work has or has not been completed. This result is

Task	Average Improvement	Best	Worst
Forage			
State vs No Communication	16%	66%	-5%
Goal vs No Communication	19%	59%	-7%
Goal vs State Communication	3%	34%	-19%
Consume			
State vs No Communication	10%	46%	-9%
Goal vs No Communication	6%	44%	-16%
Goal vs State Communication	-4%	5%	-30%
Goal vs State (low mass attractors)	-1%	23%	-19%
Graze			
State vs No Communication	1%	19%	0%
Goal vs No Communication	1%	19%	0%
Goal vs State Communication	0%	0%	0%

Table 3: Summary of performance ratios for no, state and goal communication.

important because it implies that for tasks where such implicit communication is available, explicit communication is unnecessary.

3.7.4 Summary of Results with Communication

The performance improvements each type of communication offers for each task are summarized in Table 3. Several important conclusions may be drawn:

- Communication improves performance significantly in tasks with little implicit communication (*Forage* and *Consume*).
- Communication appears unnecessary in tasks for which implicit communication exists (*Graze*).
- More complex communication strategies (Goal) offer little benefit over basic (State) communication for these tasks (i.e., display behavior is a rich communication method).

3.8 Results on Mobile Robots

The ultimate goal of this research is a working multiagent robotic system; simulation serves only as a development tool. To demonstrate the simulation results, and to move towards a completely functional society, the behaviors for *Forage*, *Consume*, and *Graze* must be instantiated on mobile robots. The target system is a group of three Denning mobile robots, George, Ren, and Stimpy. They each have three-wheeled kinematically holonomic suspensions and a ring of 24 ultrasonic range sensors. George, is a DRV-1; Ren and Stimpy are MRV-2s.

Initial results were obtained by porting tasks to Driver, a menu-driven motor schema-based reactive control system written in C.

3.8.1 *Forage*

The *Forage* task was ported and tested on Ren and Stimpy. Most of the required schemas had already been coded in Driver, but the lack of an existing omnidirectional sensor system for attractor and robot detection complicated matters. The problem was circumvented by simulating the sensor within an embedded perceptual schema utilizing shaft encoder data. Spatial locations of attractors and moving robots are maintained in continuously updated shared files. Fidelity is maintained by coding the perceptual schema so that it does not "reveal" the location of attractors or other robots until they are within sensor range.

A test with one robot, Ren, is depicted in Figure 13. The sequence shown was first videotaped and then images were captured for print from that tape later. Telemetry from the run is shown at the right of Figure 13. Initially, Ren is set up at home base. Two attractors are available for collection, marked by circles on the floor in the foreground and background. Another inactive robot, Stimpy is just off to the left. Even though Stimpy was not involved in the task directly, the **avoid-static-obstacle** schema for robot to robot repulsion was active on Ren.

Except for sensor range, parameters were set as in the baseline simulations (Table 1). Since the test area is rather small, attractor sensor range was reduced from 20 to 10 feet. This value, nonetheless, prevented Ren from immediately sensing both attractors at home base.

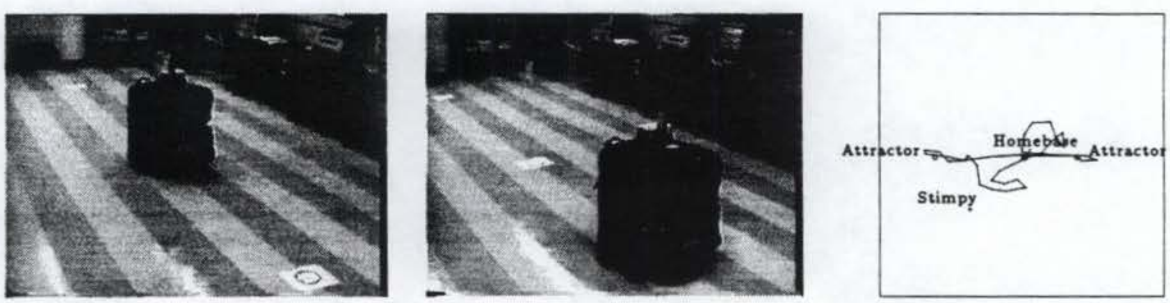


Figure 13: A Denning robot, Ren, demonstrates the *Forage* task (left). Ren tags an attractor (center). Telemetry from the Single-Agent Forage demonstration is shown at right. Home base is in the center. Two attractors are located on the left and right. The inactive robot Stimpy is in the lower left.

The foreground attractor is eight feet from home base, so at the start of the test it is immediately visible. Ren moves towards it and "tags" it in Figure 13. The notional attractor is carried back to home base. Ren transitions to *wander*. Note that the other robot, Stimpy, is located between Ren and the remaining attractor. Since *wander* includes a strong robot to robot repulsion, Ren continues to search away from the attractor. The assumption is that Stimpy would search the rest of the space, but since Stimpy is inactive and there is no communication present, the attractor might take an inordinate amount of time to be discovered. A human steps in to help. The human is able to herd Ren towards the attractor by placing his hands near the ultrasonic sensors. Once Ren gets within 10 feet of the attractor, it transitions to *acquire* (the human leaves), and then the robot tags it. Finally, the attractor is deposited at home base.

A two robot run of the *Forage* task is shown in Figure 14. Again, the parameters are those from the baseline simulation runs, except for the attractor sensor range which was set at 10 feet. The minimum range a robot could approach an obstacle was set at two feet. There are three attractors (boxes) and one obstacle (chair) in the environment. Both robots were initialized at home base. This run was made without communication. At the beginning of the run (Fig. 14), the robots enter the *wander* state, and are repulsed by each other. They immediately detect separate attractors. After tagging their respective attractors, the robots deliver them to home base. Again the robots cycle to *wander*. Only one attractor remains (in the foreground). The attractor is within Ren's sensor range, but outside Stimpy's, so Ren approaches it alone. As Ren returns the attractor to home base, it carries it within Stimpy's sensor range. Stimpy responds by approaching Ren and helping to deliver the attractor. A (hand-drawn) reconstruction of this run is shown in Figure 15.

3.8.2 Communication modes and *Consume*

All three levels of communication for the *Consume* task have been implemented and tested on Ren and Stimpy. A scenario for the two robots with one attractor was used in testing the *Consume* behavior (Figure 16). Although the scenario is simple it serves to illustrate the advantages of and the qualitative differences between the three levels communication previously described. Runs on mobile robots are directly compared with simulations of the same scenario in Figure 16.

In the test scenario, two robots and one attractor are arranged so that one robot is immediately within sensor range of the attractor, while the other is just outside sensor range. In the simulations, the attractor is 20 feet from the lower robot. If no communication is allowed, one robot should initially move towards the attractor. The other robot should move away, due to inter-robot repulsion. If communication is allowed, both robots should initially move towards the attractor since at least one of them senses it.

These predictions are borne out in the simulations shown in the top row of Figure 16. The simulations were run in the environment described earlier using the baseline control parameters (Table 1). In the case of No Communication, Robot 1 immediately moves to the attractor and begins consuming it (top left). Robot 2 moves away, and continues to search for attractors in

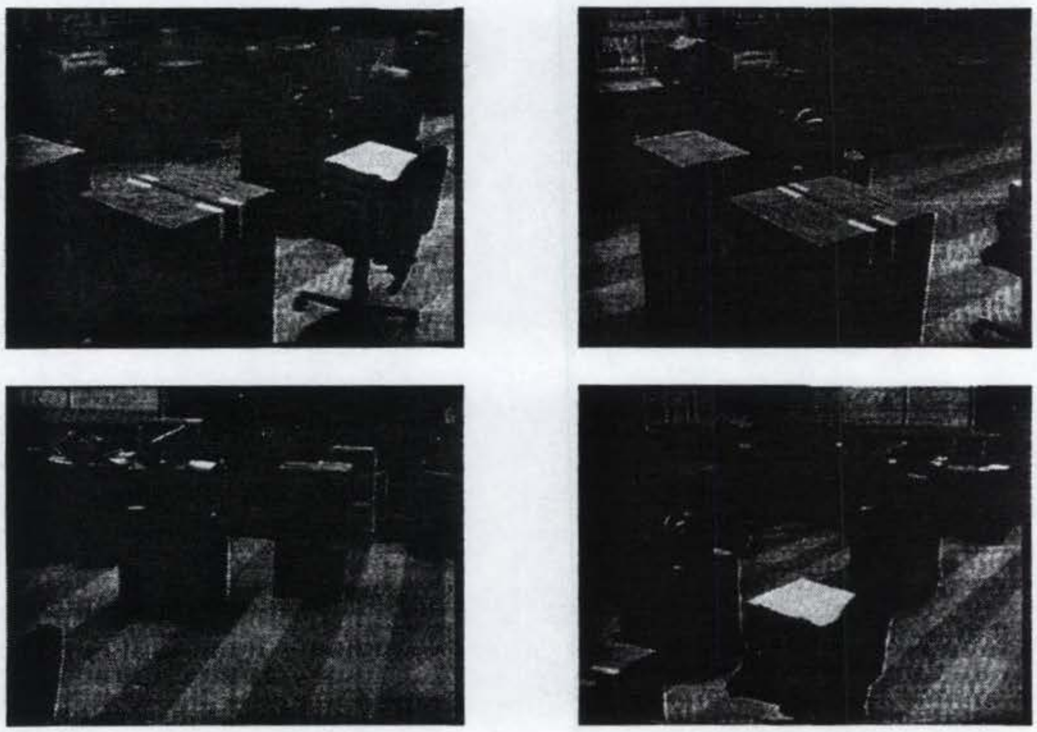


Figure 14: Two Denning robots, Ren and Stimpy, demonstrate the Forage task (upper left). Ren tags an attractor (upper right). Stimpy "tags" an attractor (lower left). Ren and Stimpy deliver the attractors to home base (lower right).

the *wander* state. Eventually it too falls within sensor range of the attractor, moves towards it, and helps consume it. In the case of State Communication (top center), Robot 1 again initially moves towards the attractor. Robot 2 begins to follow it (dotted line), then transitions to the *acquire* state (solid line) when it comes within sensor range of the attractor. Finally, in the case of Goal Communication (top right), both robots immediately move to the attractor and consume it. A qualitative difference between State and Goal Communication is visible in the paths Robot 2 takes to the attractor in Figure 16 (top row). With State Communication, Robot 2, initially outside sensor range of the attractor, makes a curved path to the attractor since it can only follow Robot 1 initially (top center). When Goal Communication is allowed, however, Robot 2 can proceed directly to the attractor (top right).

Now compare the simulations (top row) with runs on the robots Ren and Stimpy (bottom row). Since the sensor range of the robots is set at 10 feet, the scenario was altered for runs on mobile robots so that the attractor is only 10 feet away from the lower robot. The telemetry is shown at half the scale of the simulated runs to account for the smaller scale of the scenario.

Qualitatively, performance for mobile robots with No Communication is quite similar to simulated performance (Figure 16 bottom left). Initially, Ren does not sense the attractor and explores the left side of the laboratory instead. But eventually, it comes within sensor range and moves to the attractor. When State Communication is allowed Ren follows Stimpy to the attractor, making a curved path (bottom center). Finally, when Goal Communication is allowed, Ren travels directly to the attractor (bottom right).

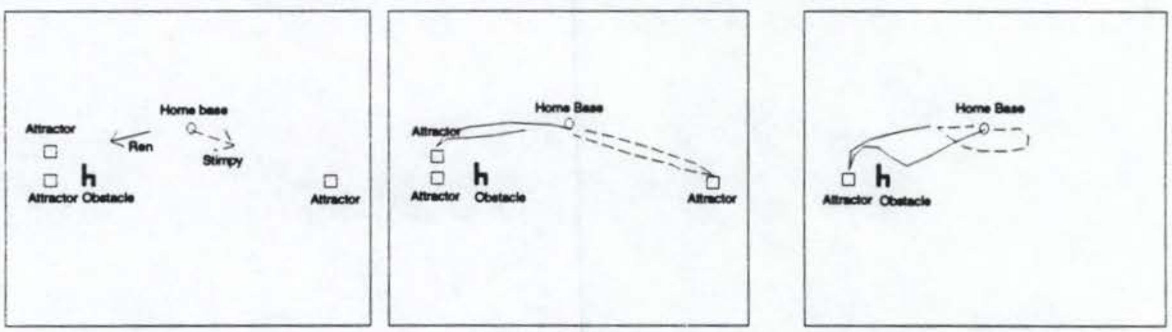


Figure 15: A reconstruction (from above) of the Forage demonstration.

The path of the lower robot for the cases of State and Goal Communication is somewhat different in simulation than on mobile robots. On mobile robots, the lower robot curves away from the upper robot much more than in simulation. This is a result of two factors. First, the scale of the telemetry re-creations are half that of the simulations. Thus, the effects of inter-robot repulsion are visually exaggerated. Second, the perceptual process for obstacle detection (a ring of ultrasonic sensors) is not sophisticated enough to ignore robots: robots are detected as robots and as obstacles. The repulsion between them is further exaggerated. This problem will be resolved as better omnidirectional sensors and perceptual processes are incorporated into our research.

3.9 Technical Summary

The impact of communication on performance in reactive multiagent robotic systems has been investigated through extensive simulation studies. Performance results for three generic tasks illustrate how task and environment can affect communication payoffs. Initial results from testing on mobile robots are shown to support the simulation studies.

The principal results for these tasks are:

- Communication improves performance significantly in tasks with little environmental communication.
- Communication is not essential in tasks which include implicit communication.
- More complex communication strategies offer little or no benefit over low-level communication.

More detailed conclusions appear earlier in this report.

Future work involves three major research thrusts. The first is concerned with societal performance in fault-tolerant multiagent robotic systems; where unreliable communication may be present and the robotic agents have the potential for failure. The second research thrust involves integrating humans more effectively with the control of a society through teleoperation. The last area includes developing novel methods for formalizing and expressing multiagent robotic systems with the goals of producing tools which will facilitate their use and to establish formally provable properties (i.e., necessary and sufficient conditions) regarding their specifications.

4. Project Assessment

The following section critiques our progress towards satisfying each of the stated project goals in the original proposal as stated in Section 2.1.

- The research on establishing our baseline results provided us an understanding of the limits of multi-agent robots in the absence of communication (see Section 3.6.4).
- Two additional communication protocols were analyzed: state and goal communication (Section 3.4). These were tested for homogeneous multi-agent robotic teams. Unfortunately time did not permit us to pursue other social organizations and this is left for future work.
- Multiple generic tasks were studied for this application (section 3.2).

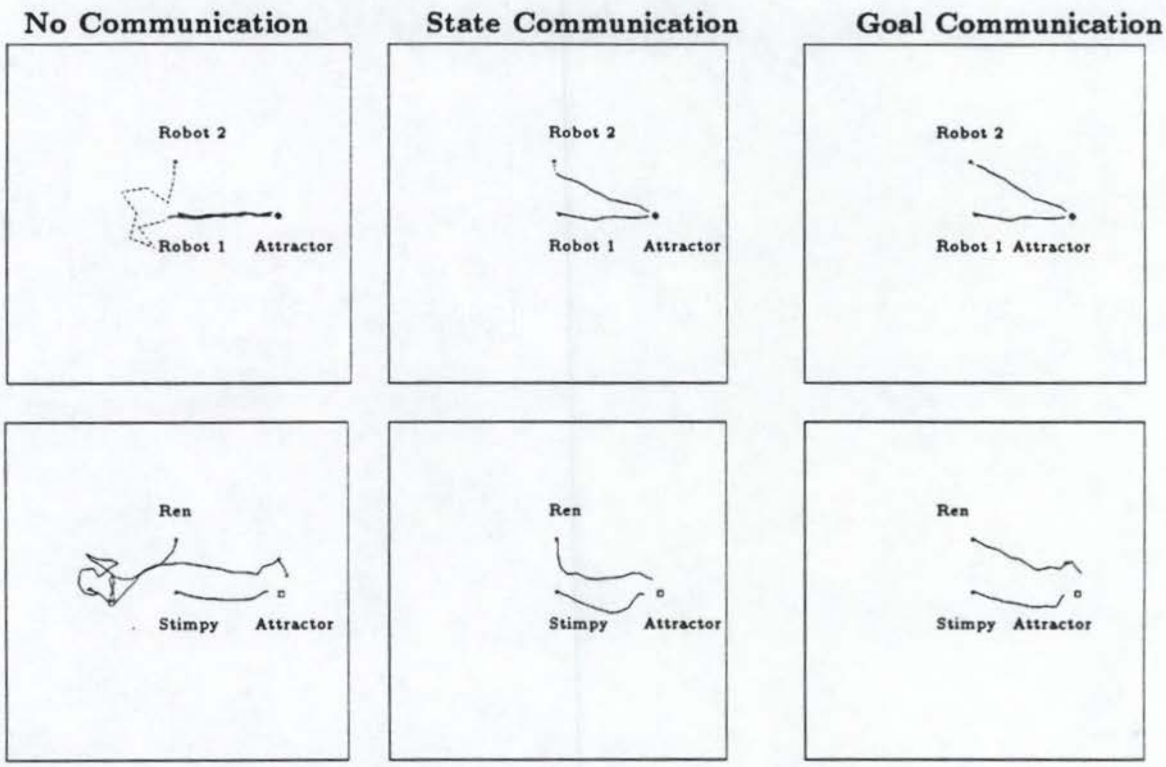


Figure 16: Comparison of simulated *Consume* task runs (top row) with runs on mobile robots (bottom row).

- The system was fielded on both our Denning Mobile Robots and on a team of small robots for the AAAI Mobile Robot competition (see next Section).

Most of the project goals were satisfied and an exciting agenda for future research was laid out. Follow-on funding from ARPA (see next Section) will enable us to continue to pursue this important avenue of research.

5. Technology transfer

Several different means were pursued for propagating the results of this project beyond our own laboratory's boundaries. These involved efforts with Industry, Academia, and the Department of Defense. These results are summarized below.

1. AT&T/CIMS Intelligent Manufacturing Laboratory
   Prof. Arkin served as Director of the above-name laboratory for the last two years and was able to leverage contributions from AT&T to construct a team of small robots that were entered in the AAAI competition below. This provided visibility within AT&T and their corporate sponsor provided strong support and encouragemnt for this effort.

2. AAAI Mobile Robot Competition
   In the summer of 1994 a team of 10 students (lead by Mr. Tucker Balch, the Graduate Research Assistant funded under this project) from three different disciplines (Computer Science, Mechanical Engineering, and Electrical Engineering) constructed three small robots that were tasked to clean up an office-like arena. Our team won the competition. An article summarizing these results appears on the following page.

3. CIMS IAB
   Twice per year we have had the opportunity to present our research before the Georgia Tech Computer Integrated Manufacturing Systems Program's Industrial Advisory Board. This has included actual demonstrations of our robotic hardware in operation.

4. ARPA/ONR Grant
   The results of this research is now being applied in the context of ARPA's Demo II mission and will be fielded on as many as four HUMMV's operating at Fort Hood in the summer of 1996 and carrying out military scout missions. Our particular role in that multi-university/industry project is to provide formation behaviors, teleautonomous control methods, and mission specification tools for multi-robot teams operating in a military environment.

ghostv

new student ideas.

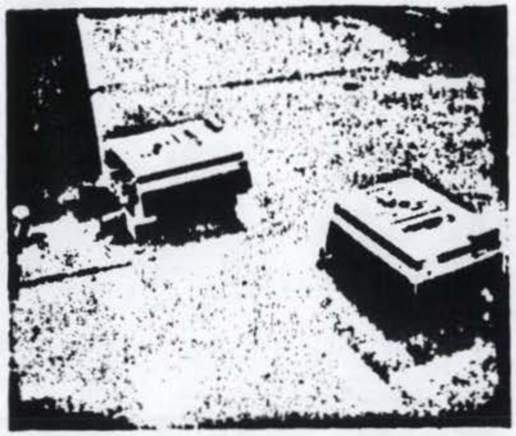
Tech Robots Sweep International Competition

Ganymede, Io and Callisto are cleaning up. In fact, they are the nation's best robotic office cleaners. The awesome threesome are small robots that look like miniature tanks. Designed by a group of Georgia Tech students, the team of robots recently won the third annual International Mobile Robot Competition, in Seattle. The Georgia Tech robots were the first robots to enter the competition as a cooperating team.

The contest, sponsored by the American Association for Artificial Intelligence (AAAI), required the robots to clean up an office littered with soda cans, coffee cups and large paper wads in 10 minutes, or to navigate an office using an electronic map. The purpose of the annual competition is to bring industry and academic units together and challenge them with a "real world" task.

"Our approach was to build lots of low-cost robots instead of a single very expensive one. Our research in simulation showed that we should get the job done faster and more reliable that way," said Tucker Balch, team leader. "Also, there are lots of examples of successful teamwork in nature—ants and bees for instance. I think our robots demonstrated that robot teams are a good idea."

Georgia Tech's robotics team, supported by the CIMS/AT&T Intelligent Mechatronics Lab, programmed its robots with a "reactive" system called motor schema-based control. Motor schemas are basic behaviors such as avoiding obstacles and moving to a goal. More complex behaviors are attained by combining several motor schemas. To clean up the office, the robots progressed from one behavior to another to gather trash.



Callisto and Ganymede swept the competition taking top honors in a national student competition, sponsored by American Association for Artificial Intelligence (AAAI)

The bright green robots easily see one another so that they can cooperate. This allows them to move away from each other, preventing interference and covering more area faster. A tiny color camera guided the robots to grab trash with a specially designed gripper. Once a robot had a piece of trash, it searched for a trash can using vision. After it located a trash can, the robot moved to it and dropped the trash nearby. Even for Georgia Tech's winning team, the competition wasn't without a hitch. At times the robot's vision was fooled by dark shadows and it grabbed non-trash objects such as table legs. However, the team programmed the robots so only the objects that moved were considered to be trash. Since the trash cans were

project-centered classroom, different ... student groups might work on different p... relating to the content and skills that need learned, but each specific to the interests ... edge of the students in the group.

Kolodner's conclusion is that large ... curriculum should be student-centered a... based, in which students learn by solving problems. The teacher assists by choosi...

Robots,

Continued from Page 1

See Robots page 3

black, the robots were programmed to move toward the darkest objects to deliver trash. However, there was confusion caused by dark shadows under tables. The result—Io, Ganymede and Callisto, like Dennis the Menace, sometimes hid trash under furniture instead of throwing it away.

The Georgia Tech team was an interdisciplinary group of students and engineers led by Balch and advised by Professor Ron Arkin. Team members included, from the College of Computing: Balch, Gary Boone, Harold Forbes, Ray Hsu, Doug MacKenzie, and Juan Carlos Santamaria; from the School of Mechanical Engineering: Erik Blasch; from Georgia Tech Research Institute: Tom Collins and Dave Huggins; and Claudia Martinez, a visiting student from Mexico.

6. Publications and Presentations to date resulting from this Award

6.1 Published Papers

- Balch, T. and Arkin, R.C., "Communication in Reactive Multiagent Robotic Systems", *Autonomous Robots*, Vol. 1, No. 1, pp. 27-52, 1994.
- Arkin, R.C. and MacKenzie, D., "Temporal Coordination of Perceptual Algorithms for Mobile Robot Navigation", *IEEE Transactions on Robotics and Automation*, Vol. 10, No. 3, June 1994, pp. 276-286.
- Arkin, R.C. and Ali, K., "Integration of Reactive and Telerobotic Control in Multi-agent Robotic Systems", *Proc. Third International Conference on Simulation of Adaptive Behavior, (SAB94) [From Animals to Animats]*, Brighton, England, Aug. 1994, pp. 473-478.
- MacKenzie, D. and Arkin, R.C., "Formal Specification for Behavior-based Mobile Robots", *Mobile Robots VIII*, Boston, MA, Nov. 1993, pp. 94-104.
- Arkin, R.C., Balch, T., and Nitz, E., "Communication of Behavioral State in Multi-agent Retrieval Tasks", *Proc. 1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, May 1993, Vol. 3, pp. 588-594.
- Arkin, R.C. and Hobbs, J.D., "Dimensions of Communication and Social Organization in Multi-Agent Robotic Systems", *From animals to animats 2: Proc. 2nd International Conference on Simulation of Adaptive Behavior*, Honolulu, HI, Dec. 1992, MIT Press, pp. 486-493.
- Balch, T. and Boone, G. and Collins, T. and Forbes, H. and MacKenzie, D. and Santamaría, J.", "Io, Ganymede and Callisto - a Multiagent Robot Trash-collecting Team", submitted to AI Magazine, 1994.

6.2 Invited Talks (no proceedings)

- AMCA/IEEE International Workshop on Neural Networks Applied to Control and Image Processing, "Control and Communication for Reactive Multirobot Systems", Mexico City, Nov. 1994.
- Emory University Psychology Seminar, "Reactive Multi-agent Robotic Systems", Atlanta, GA, Nov. 1994.
- 14th UGV/Demo II ARPA Workshop, "Cooperating Multi-agent Reactive Robotic Systems", Vail, CO, March 1994.
- Georgia State University Biology Seminar, "Cooperating Multi-agent Reactive Robotic Systems", Atlanta, GA, Jan. 1994.

- Conference on Prerational Intelligence, "Cooperating Multi-agent Reactive Robotic Systems: Experimenting with Autonomous Agents", University of Bielefeld, Germany, Nov. 1993.
- X National Conference on Artificial Intelligence, "Multi-agent Reactive Robotic Systems", Mexico City, Sept. 1993.
- IJCAI Workshop on Dynamically Interacting Robots, "Communication in Multi-agent robotic systems: When is enough enough?", Panel Discussion (moderator and presenter) on Communication in Multi-agent Robotic Systems, *13th International Joint Conference on Artificial Intelligence*, Chambery, France, Aug. 1993.
- 1993 NSF Coordination Theory and Collaboration Technology Workshop, "Cooperation and Communication in Multi-agent Reactive Robotic Systems", Arlington, VA, July 1993.
- 1993 IEEE International Conference on Robotics and Automation, "Birds do it (flock), Bees do it (swarm), Even Educated Fleas Do it (Circus)", workshop on "Needs for Research in Cooperating Robots", Atlanta, GA, May 1993.

REFERENCES

[1] Arkin, R.C., 1989. Motor Schema Based Mobile Robot Navigation, *International Journal of Robotics Research*, vol 8(4), pp. 92-112.

[2] Arkin, R.C., 1992. Cooperation without Communication: Multi-agent Schema Based Robot Navigation, *Journal of Robotic Systems*, Vol. 9(3), pp. 351-364.

[3] Arkin, R.C., *et. al.* , 1993. Buzz: An Instantiation of a Schema-Based Reactive Robotic System, *Proc. International Conference on Intelligent Autonomous Systems: IAS-3*, Pittsburgh, PA., pp. 418-427.

[4] Arkin, R.C., Balch, T., Nitz, E., 1993. Communication of Behavioral State in Multi-agent Retrieval Tasks, *Proc. 1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, vol. 1, p. 678.

[5] Arkin, R.C. and MacKenzie, D., 1994. "Temporal Coordination of Perceptual Algorithms for Mobile Robot Navigation", to appear in *IEEE Transactions on Robotics and Automation.*

[6] Arkin, R.C., Murphy, R.R., Pearson, M. and Vaughn, D., 1989. Mobile Robot Docking Operations in a Manufacturing Environment: Progress in Visual Perceptual Strategies, *Proc. IEEE International Workshop on Intelligent Robots and Systems '89*, Tsukuba, Japan, pp. 147-154.

[7] Balch, T., Arkin, R.C., 1993. Avoiding the Past: A Simple but Effective Strategy for Reactive Navigation, *Proc. 1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, vol. 1, pp. 678-685.

[8] Clark, R.J., Arkin, R.C., and Ram, A., 1992. Learning Momentum: On-line Performance Enhancement for Reactive Systems. *Proc. 1992 IEEE International Conference on Robotics and Automation*, Nice, France, May 1992, pp. 111-116.

[9] Helmbold, D. and McDowell, C., 1990. Modelling Speedup(n) Greater than n, *IEEE Transactions on Parallel and Distributed Systems*, vol 1(2), pp. 250-256.

[10] MacKenzie, D. and Arkin, R.C., 1993. Formal Specification for Behavior-Based Mobile Robots, *Proc. SPIE Conference on Mobile Robots VIII*, Boston, MA, pp. 94-104.

[11] MacKenzie, D.C. and Balch. T.R., 1993. Making a Clean Sweep: Behavior Based Vacuuming. *Working Notes of 1993 AAAI Fall Symposium: Instantiating Real-World Agents.* Raleigh, N.C.

[12] Mataric, M., 1992. Minimizing Complexity in Controlling a Mobile Robot Population. *Proc. IEEE International Conference on Robotics and Automation*, Nice, FR, May 1992.

[13] Moynihan, M. 1970. Control, Suppression, Decay, Disappearance and Replacement of Displays. *Journal of Theoretical Biology*, 29:85-112.

[14] Pearce, M., Arkin, R.C., and Ram, A., 1992. The Learning of Reactive Control Parameters through Genetic Algorithms, *Proc. 1992 International Conference on Intelligent Robotics and Systems (IROS)*, Raleigh, N.C., pp. 130-137.